Air pressure and the building envelope

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Abstract

There are significant differences in air pressure between the interior and exterior of a building envelope and between lower and upper levels of multi-storey buildings. The effects of air pressure and differences on moisture movement are poorly understood by design and construction professionals.

Air pressure gradients and cycles cause many structural and moisture problems, such as moisture penetration and condensation within the construction cavities of roofs, exterior walls and within and around windows.

Pressure differences are also indirectly responsible for corrosion of metal fasteners, rotting wood, masonry efflorescence, brick and stone spalling, excessive energy use and poor smoke control. Air pressure differences are induced by five forces—stack effect, fan pressurization, wind cycling, barometric cycling and thermal cycling.

This article examines the sources of pressure and pressure gradients and the characteristics of buildings, particularly envelope cavities or voids, which are subject to these five forces. It also addresses the ways design can combat the negative effects of pressure and air pressure differences. This article also explains the dynamic buffer zone (DBZ), a recent concept for control of envelope moisture.

Objectives

After reading this article, you should understand:

1. How and where pressure differences drive moisture within buildings and their envelopes
2. How the main driving forces which create these pressure differences contribute to moisture problems, and their relative significance
3. How to do basic calculations to determine pressure differences
4. Strategies to offset the problems of pressure differences due to mechanical, thermal, barometric and stack effects.

Air pressure and air pressure differences

Atmospheric pressure at ground level is determined by the weight of the column of air above the surface of the earth which is about 560 km thick. Air pressure (or weight per unit area) varies with height above ground. Sea level is the reference altitude, at which the air pressure is about 101,300 Pa or 101.3 kPa.

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Atmospheric pressure decreases as height above sea level increases. At about five km above sea level, atmospheric pressure drops by about half, to 54.0 kPa.

Air pressure difference results from variations in absolute pressure between one area and another. The variations can be the result of differences in air density, such as stack effect in winter, or by wind impacting on a building surface. Changing barometric pressure and air temperature changes in sealed cavities can also cause variations. Mechanical means, such as fan pressurization for ventilation or the operation of a DBZ system, can also create air pressure variations.

An air pressure difference causes two important effects on buildings: a mechanical force on building components and air being forced through an opening, cracks or leakage path.

The effects of pressure differences

The first significant effect of pressure differences, the force acting on surfaces, may be a weak force, as in stack effect or fan pressurization, which are generally around 10 Pa to 50 Pa. However, even a weak pressure difference over a sustained period may cause fatigue and failure of building envelope components. On the other hand, the force may be strong, such as force from wind, which can rupture, tear or displace cavity materials, lift a roof membrane and even pull off wall claddings. While this force is generally rare, designers must consider it, as the design load can reach 1,000 Pa to 2,000 Pa over 10 to 30 years. Designers cannot ignore the effects of stack or fan pressurization, as they can cause severe moisture damage to the building envelope.

The other significant effect of air pressure difference is air leakage through openings, cracks and joints in the building envelope. When higher pressures act on the outdoor side of the envelope air leaks inward—*air infiltration*. If the air pressure difference creates higher pressure on the inside of the building envelope, air leaks outwards—*air exfiltration*. Air leakage causes many problems, such as condensation, corrosion, icicles on outside surfaces, brick spalling, difficulty in controlling indoor temperature and humidity in addition to energy losses.

Cavities and the building envelope

The building envelope which separates the indoor environment from the outdoor environment, limits the transfer of heat, air, moisture, noise, fire and dust. To be effective, the building envelope must contain the pressure within the building and manage the pressure differences across the building envelope. It is especially important that the envelope prevents or limits air leakage.

Pressure and pressure differences act on all parts of the building envelope, but their effects generally occur in the envelope's construction cavities. This is why there should be critical analysis of construction cavities. For example, a traditional roof assembly may be composed of a layer of waterproofing, insulation, a vapour retarder and a structural support deck. Of concern is the roof cavity—the space between the waterproofing and the deck—specifically, the actual volume of the roof cavity (*see*

Figure 1.) With fibrous roof insulation, the volume of the roof cavity may be equal to, or greater, than 95 per cent of the nominal cavity volume. With rigid insulation, the effective roof cavity volume is smaller but still significant. The importance of the actual cavity volume is explained in the section on barometric and temperature cycling.

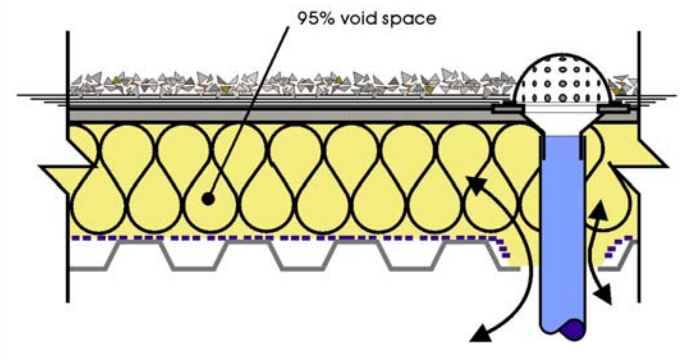

FIG. 1 - BUR ROOF SYSTEM

Wall assemblies—precast clad exterior walls, metal and glass curtain walls, exterior masonry walls, stucco and EIFS walls, steel or aluminum panel wall systems—contain cavities, which include cavities in the stud spaces of wood and steel stud framing, cavities between the cladding and sheathing and cavities in parapets, soffits, and column covers (*see* Figure 2.)

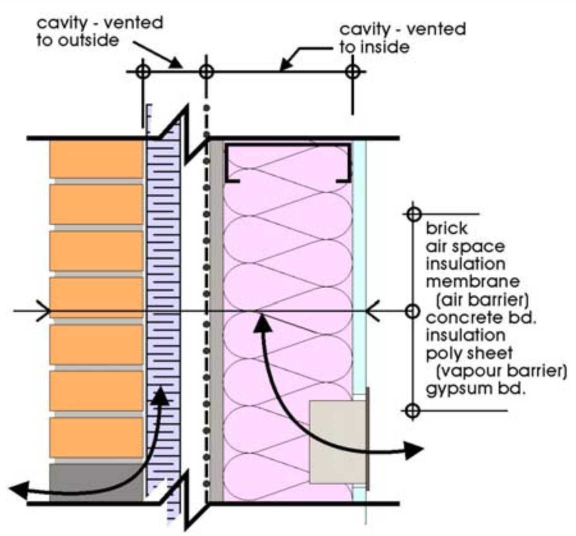

FIG. 2 - SSBV WALL SYSTEM

Windows are a special example, because they require a cavity between the window frame and the rough wall opening and, in hermetically sealed glazing units, a glazing cavity within the insulating glass units. In a standard aluminum curtain-wall system there are glazing cavities between the frame and sealed-glass units.

Pressure and pressure differences have their most significant effects on the materials defining the construction cavities of the building envelope. These effects then extend outwards to the cladding and inwards to the indoor finishes. While the visible symptoms of envelope problems appear first on the outside or inside surfaces, the most damage generally occurs within the concealed spaces of roof and wall cavities.

Understanding stack effect

Stack effect is a temperature-driven phenomenon, which is especially noticeable in cold weather, when warmer indoor air, which is more buoyant than the colder outdoor air, tends to rise in the building. This produces a difference in air pressure between the indoor space and the outdoor environment at the roof and upper exterior walls. This pressure difference causes the interior air to push out through cracks and openings in the upper parts of the building envelope, including the roof and upper ends of the exterior walls. At the same time, while air is exfiltrating from the top of the building, there is a reverse air-pressure difference at the base of the building. This reversed pressure may induce air infiltration. This phenomenon is the stack (or chimney) effect. The location on the exterior wall where the air pressure difference reverses from infiltration to exfiltration, is defined as the neutral pressure plane (npp) (*See* Figure 3).

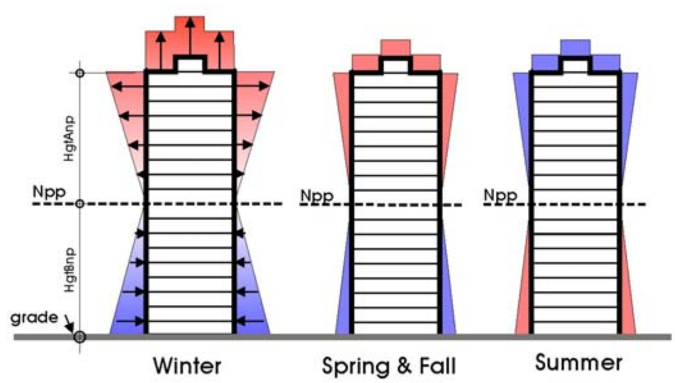

FIG. 3 - STACK EFFECT

To a lesser extent, indoor humidity also causes air to rise or sink because *moist air is lighter than dry air*. Therefore, moist air of the same temperature as dry air rises because it is less dense than the dry air (the hydrologic cycle). The physics sections that follow give a more detailed explanation of stack effect.

When the indoor air is humid and the outdoor air temperature is below the dew point temperature of the indoor air, there can be condensation where air exfiltrates within the construction cavities or behind the cladding. The consequences are frost or moisture buildup within parapets, icicles on claddings, corrosion of metals, freeze–thaw damage to masonry, mold in wood-frame walls and increased energy costs. Similarly, the infiltrating air passing through the exterior wall cavities at the base of the building may cool indoor surfaces to below the dew point of the indoor air. This may lead to surface condensation on indoor surfaces, freezing of pipes in wall cavities and uncontrollable indoor temperature and humidity.

How to determine the stack effect pressure difference

The following are the calculations to determine pressure difference due to stack effect between the inside and outside of walls or roof.

First, determine the height of the building (H) above grade.

Second, arbitrarily select a neutral pressure plane height (H_{npp}) above the grade of the building, usually one or two storeys above grade in a multi-level building. In a low building select grade as the neutral pressure plane (npp).

Third, select a given height above (or below) the neutral plane, such as the roof plane.

Compute the pressure difference at that plane as follows.[1]

$\Delta P_s = d_i g(H-H_{npp})(T_i-T_o)/T_o$

where ΔP_s=stack effect pressure difference (Pa)

and d_i =density of indoor air, kg/m^3

and g=gravitational acceleration, 9.81 m/s^2

and H= height of plane above (or below) Npp, m

and H_{npp}=height of neutral pressure plane, m

and T=absolute temperature, Kelvin

and $_i$= indoor, $_o$= outdoor

For a 60-m (197 ft.), 20-storey building with a neutral pressure plane at about the 4th storey or 12 m (40 ft.) from grade, in winter with an outdoor temperature of -20°C and an indoor temperature of +20°C, the stack effect at the top of the exterior wall (and roof plane) is:

$\Delta P_s=d_i g(H-H_{npp})(T_i-T_o)/T_o$

$=1.2\times9.81\times(60-12)\times[(273+20)-(273-20)]/(273-20)$

=89 Pa

The location of the neutral pressure plane when the wind speed is zero depends on the characteristics of the building envelope—the number and distribution of openings, the resistance of the openings to airflow and the resistance to vertical airflow within the building. Assuming that the openings in the exterior walls are uniformly distributed, of equal airflow resistance and there is no indoor resistance to airflow between floors, the neutral plane will occur at the mid-height of the building.

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1 1997 *ASHRAE Handbook Fundamentals*, SI Edition, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, Atlanta, GA 30329, Tel (404) 636-8400, website http://www.ashrae.org

The location of the neutral pressure plane is not static. It may be displaced up or down by the action of wind and particularly by the design and operation of the ventilation systems. Mechanical engineers commonly intend a slight pressurization of a building, which can cause downwards displacement of the neutral pressure plane. This fan pressurization is intended to reduce the infiltration of outdoor air at lobby level to better control the indoor temperature in winter. It also reduces the number of floors exposed to possible infiltration problems.

Problems caused by stack effect

Stack effect occurs in all buildings in which a temperature difference exists. It cannot be prevented, removed or neutralized. It can be shifted and even broken up to limit its effects on the building envelope.

The most pronounced effect, and potentially damaging result, is at the upper exterior walls, the roof and at or near grade.

Air exfiltration at building parapets

This exfiltration may cause the buildup of condensation in the parapet cavities as wetness or corrosion staining of facades, and as frost in winter. This frost then melts and drains back to the inside of the building in spring. Stack effect is also known to cause problems at grade level, for example, cold rooms at floors below the npp and frozen pipes in exterior walls and grade-level soffit cavities.

Stack effect does not result in large pressure differences. A typical pressure difference at the roof of a 10-storey building with an npp one storey above grade that is exposed to an outdoor temperature of -10˚C is 38 Pa. What makes stack effect significant is the sustained—for months over a winter—unidirectional pressure difference. This sustained pressure difference may result in significant moisture accumulation in cavities and energy loss. It can also cause some air barrier materials to detach or peel from their substrate. These materials must be attached mechanically to prevent this type of failure.

Fan pressurization

Stack effect is a temperature-driven phenomenon and cannot be avoided. When stack effect is reduced at grade by the fan pressurization of a building, there is a corresponding increase in pressure difference at the top of the building. Fan pressurization is accomplished by increasing makeup air or by reducing exhaust air. Typical fan pressurization may increase or reduce building pressure by as much as 50 Pa. Similar to stack effect, fan pressurization is generally unidirectional and often causes unnecessary exfiltration or infiltration through the building envelope, resulting in many types of cavity moisture problems.

Warm weather condensation

Stack effect also occurs in summer, when the driving forces reverse the airflow to cause infiltration at the roof and upper walls while causing exfiltration at the lower levels. In southern latitudes where the outdoor temperature remains hot and humid for prolonged periods, the roofs and exterior wall cavities often exhibit wetness due to condensation of the outdoor humid air on colder inside finishes of air-conditioned rooms. This wetness may cause premature corrosion of metals, rotting of wood and the production of various mold problems. It also causes a significant loss of air-conditioned air and high energy consumption.

Design strategies for stack effect

Strategies to reduce the problems associated with stack effect include limiting indoor humidity levels, improvements in the airtightness of the building envelope, use of revolving doors or air locks at entrance level and forming more airtight compartments at different floor levels so the floors perform as horizontal barriers to vertical airflow. Fan pressurization or depressurization has also been used, but while pressurization may minimize one problem, it tends to increase another. Fan pressurization is discussed further in the next section.

Providing the building envelope with a high quality air barrier is a moderately effective solution. In this design strategy, it is particularly important to join the roof and exterior-wall air barriers regardless of the type of roof, roof overhangs, exterior wall or building height. The air barrier materials must be robust and properly attached to resist wind loads, sustained stack effect loads and fan pressurization loads for the life of the building, or they must be accessible for periodic maintenance and service. If the air barrier systems are not designed to sustain these loads, the air barrier design will not comply with the requirements of the building code. More important, the air barrier system will fail prematurely.

Understanding fan pressurization

Mechanical systems continue to improve in quality and to provide reliable ventilation and humidification. Combining mechanical ventilation systems with air conditioning has also encouraged the use of fixed windows instead of operable windows because they allow better control of indoor conditions during hot weather. In addition, fans are also used to pressurize buildings to lower the neutral pressure plane (npp) closer to the main entrance and lobby levels to reduce the pressure differences at entrances. (*See* Figure 4.)

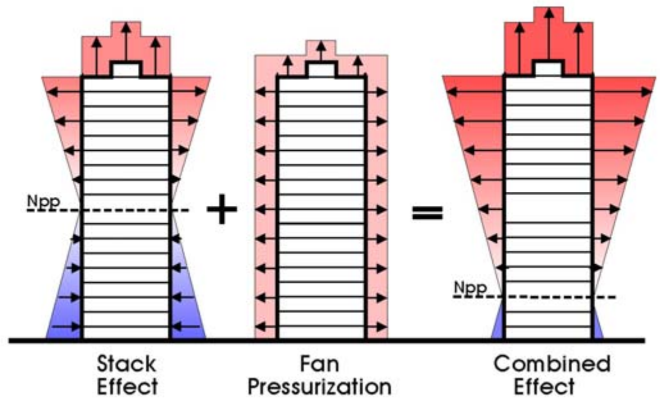


FIG. 4 - FAN PRESSURIZATION

Fan pressurization may have solved a multitude of performance problems when buildings were uninsulated and poorly sealed. But modern buildings are well insulated and often well air-sealed compared to buildings of 10 years ago. In turn, the combination of increased fan pressurization and improved building envelope airtightness has given rise to a new set of problems. One is the oversizing of mechanical equipment for heating, cooling and ventilation due to over-estimated loads, which results in higher-than-necessary capital expenditures. Others include out-of-range pressure sensors, which do not adequately control lobby pressure, resulting in hard-to-close lobby doors. In addition, air pressure differences occur across the exterior walls and roof due to fan operations, which cause unbalanced supply-and-exhaust flows, particularly during energy-conservation cycles. This is particular to a Variable Air Volume (VAV) air -handling system, which delivers variable air supply rates to building spaces. Unless the variable supply is slaved to a variable exhaust, building pressurization will vary constantly and the npp will also vary constantly. This is of little importance to a very leaky building, but it can be problematic in a tight building.

Similarly, during an energy-conservation cycle, the reduction of makeup air at night without a corresponding reduction in the exhaust air, produces an unnecessary negative pressure difference across the exterior walls and roof. This may cause temperature or humidity control problems, increased heating or cooling requirements and possibly surface condensation at window frames.

However, by far the most significant problem with ventilation system is over-pressurization of the building. This greatly increases air exfiltration at sensitive locations of the building envelope such as roofs, walls and windows. For the envelope of existing heritage buildings, it is particularly risky to retrofit those buildings with new ventilation and humidification equipment without a corresponding upgrade program to the building envelope and sufficient flexibility of the ventilation design controls to adjust pressurization or depressurization.

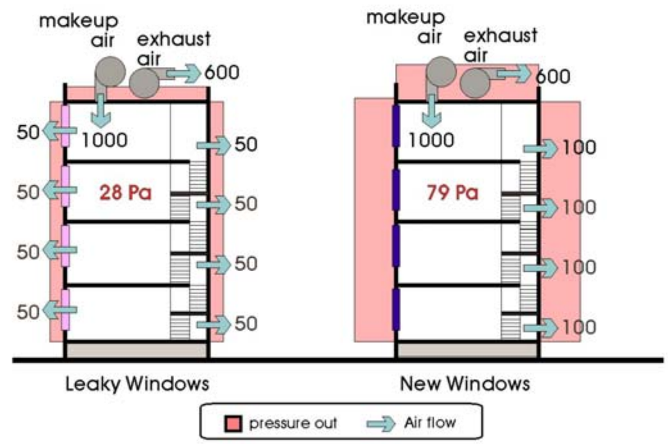


FIG. 5 - PRESSURE & FLOW BALANCE

Envelope pressure difference due to ventilation rates

Building envelope pressurization is the result of an unbalanced ventilation rate between the makeup air supply and the air that is exhausted from the building. If the building makeup air exceeds the building exhaust air, the difference in ventilation rate will increase building pressure to cause air exfiltration through envelope holes equal to the difference in ventilation rates. If the total area of the openings, holes and cracks is large, the resulting pressure difference at the building envelope will be small. If the total area of the openings, holes and cracks is small, the pressure difference may be large (*see* Figure 5). Leakage through a building envelope is generally unintentional but it can only be limited by careful construction to a minimum standard, which must be verified by testing. Further information on air barrier design, construction and testing can be found in the articles "*Design Considerations for an Air Barrier System* and *Guidelines for Delivering Effective Air Barriers* which are part of this series. To estimate the resultant pressure difference across a building envelope from an audit of the ventilation rates and the leakage areas of the envelope, use the following equation:[2]

$Q=C_d A (2 \Delta P/d)^{0.5}$ or

$\Delta P=(d/2)\times (Q/(C_d A))^2$

where ΔP=pressure difference across opening, Pa

and Q=airflow rate, m^3/s

and C_d=discharge coefficient for opening, dimensionless (0.6)

and A=cross-sectional area of opening, m^2

and d = density of air, kg/m^3 (about 1.2 kg/m^3)

Assume that a six-storey building has a makeup air (a fresh air supply) rate of 1.0 m^3/s (1000 l/s) and an exhaust rate of 0.5 m^3/s (500 l/s). Further assume that the equivalent

2 *ASHRAE Fund.* 97, p 25.11, "Airflow through openings"

leakage area of the building envelope is 0.1 m^2. Therefore the air leakage rate Q_f through the leakage openings of the building envelope is:

Q_f = makeup-exhaust =1.0 m^3/s-0.5 m^3/s= 0.5 m^3/s

and the pressure difference across the building envelope is computed as follows:

$\Delta P=(d /2)\times(Q_f/(C_d\ A))^2$

$\Delta P=(1.2/2)\times(0.5/(0.6 \times 0.1))^2$

$\Delta P=41.6$ Pa

In terms of structural loading, this is not a large air pressure difference across the building envelope. However, it is a significant air pressure difference with respect to the operation of the building. It could result in a many problems, including lobby doors not closing easily, excessive exfiltration at openings, holes and cracks, which could cause icicles to form on the cladding, moisture in cavities, premature corrosion of anchors, spalling of masonry, and so on.

If the leakage area of the building envelope had been larger, for example, 0.3 m^2, then the pressure difference would be 4.7 Pa, a negligible difference. This explains why older (leaky) buildings exhibited small pressure differences from fan pressurization and that newer (tighter) buildings may exhibit large pressure differences from the same fan pressurization.

While the total air leakage rate (Q_f) is the same in both cases, the distributed leakage area in the second case is three times larger than the first, thereby reducing the moisture transfer (and condensation) at any one leak location. On the other hand, if the building envelope were tighter, there would be approximately twice as much moisture transferred through the remaining openings, which could result in condensation and potential moisture damage where there was none before.

Fan pressurization must be re-evaluated if the above problems are to be avoided. Ventilation design is complex. Consideration must be given to the balance of the total makeup and total exhaust air during all scheduled ventilation programs, including:

- Day-night schedules,
- Weekday schedules
- Weekend schedules,
- Seasonal schedules,
- Energy-conservation programs,
- Programmed and manual set-up ventilation options,
- Scheduled seasonal operations, such as free cooling and controlled indoor humidity levels—all based upon climate conditions and building envelope characteristics.

To prevent moisture concentration at envelope openings, the answer is not more openings in the envelope but balanced ventilation rates so that a neutral pressure or slightly positive pressure is achieved at lobby level at all times. More openings increase energy costs and cause greater difficulty in attaining adequate temperature and humidification control. It would be better still to provide adequate controls so that owners and operators may adjust pressurization to optimum levels for the building envelope characteristics and the climate conditions of the time of year.

There must be increased discussion of these issues between the architect and the ventilation engineer. Compromises may be required but the airtightening of the envelope must not be one of the compromises.

Ventilation design strategies

- Provide balanced ventilation in all new buildings at or near lobby levels.
- Provide adjustment controls so that the building operator can mechanically limit induced pressure differences at individual floors that have not yet been leased. This is because makeup or exhaust ventilation may not be provided at unleased floors.
- Provide better humidification control. In large buildings, indoor humidity is also stored in the building materials, thereby causing resistance to change. When cold weather arrives, it is often too late to change a setting before condensation damage occurs at cold surfaces. For this reason, it would be helpful to program a humidity-level anticipator with a ramped control function to reduce stored humidity and to attain lower humidity levels as lower outside temperatures arrive.
- Provide balanced pressure at or near lobby levels and maintain balance throughout scheduled operations, including economizer and energy - conservation cycles.

Understanding wind pressure

As wind hits the facade of buildings, its velocity is abruptly exchanged for an increase in pressure, or push on the building facade. The maximum increase in pressure on the facade where the wind is stopped is called the *stagnation pressure*. When an obstructing building impedes the wind, it will cause an increased pressure on the face of the building. However, while the wind may stagnate on the windward side, it will most likely increase in velocity along the sides and top of the building. In these areas, the pressure will be reduced, thereby causing a suction or pull on the building façade. (*See* Figure 6.)

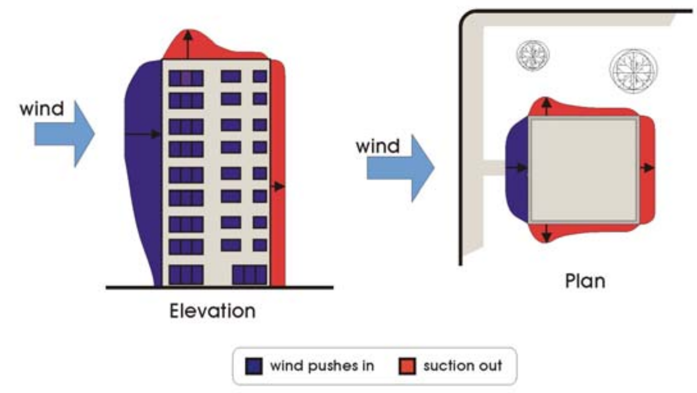


FIG. 6 - WIND PRESSURE AROUND BUILDINGS

The indoor air pressure of a building may increase or decrease with wind speed depending on the number and location of openings in the envelope. Generally, if the openings are uniformly distributed on all sides of the building, the resultant indoor pressure is slightly lower than the ambient barometric pressure. The result is a slightly increased pressure difference at the windward side and a slight decreased pressure difference on all other sides, including the roof.

These pressure differences induce air leakage. This wind driven air leakage is inward on the windward side and outward on all other sides when there is no stack effect or fan pressurization at work. Research studies have shown that wind is not the dominant force driving air leakage, but it can account for up to 25 per cent of the air change rate on a seasonal basis. However, the most important aspect of wind pressure is its structural loading. This loading is usually small, but on occasion it may reach high values, high enough to cause structural damage to roof, exterior walls and windows. It may also rupture air barrier assemblies and displace materials in exterior walls. Although the design of the building structure is the domain of the structural engineer, the architect needs to involve both the structural and the ventilation engineer with the characteristics of the roof, exterior walls and windows.

Understanding wind loads on buildings

The pressure exerted by wind striking a surface is a function of the wind speed and the density of the air. The pressure of wind stagnating on a building facade may be determined from the following equation:[3]

$P_{w=}1/2 \times dV^2$

where P_w=the stagnation pressure of wind, Pa.

and d=density of air, kg/m^3, (about 1.2 kg/m^3),

and V=velocity of the air, m/s.

3 ASHRAE Fund. 97

For example, an 11.1 m/s (40 kmh or 25 mph) wind speed having an air density of 1.2 kg/m^3 may result in a stagnation pressure of:

$P_w = ½ \times 1.2 \times (11.1)^2$

$= 74$ Pa

The leakage of air due to wind effects may be large at times but generally not as significant as that which occurs due to either stack effect or fan pressurization. This is because wind is sporadic, while stack effect and fan pressurization are sustained over long periods, in winter. However, large wind pressure loads are very important in the structural design of the air barrier for the building envelope. As such, air barriers must be designed and constructed to withstand the design wind loads in Part V of the 1995 National Building Code of Canada, (1997 OBC in Ontario).

Wind pressure and wind loads are important to strength of materials, components and assemblies. Thus, wind causes air leakage but not as much as stack effect or fan pressurization, except through damage caused to air barrier assemblies that are not sufficiently strong. There is more information on air barrier design and construction in two articles in this series: *Design Considerations for an Air Barrier System* and *Guidelines for Delivering Effective Air Barriers*.

Designing for wind loads

To be effective and durable, the air barrier system must be designed to withstand the design wind loads, both positive and negative, as defined in the National building Code of Canada, 1995 edition, for cladding systems. Membranes must be supported; panels and board products must transfer wind loads through fasteners and joint membranes must be mechanically attached and flexible at movement joint locations.

The air barrier of a building envelope is an integral part of a *rainscreen* wall system. The *rainscreen* system performs best when the air barrier system is rigid enough to resist the forces of wind gusting without excessive deflection.

Barometric pressure

Another way that air pressure change affects the building envelope is through barometric pressure cycling, which can cause wetting of cavities by condensation of humidity in the air. As barometric pressure falls with varying weather conditions, the pressure on the outside surfaces of a construction cavity also fall. If the cavity is sealed so that no air can enter or leave it, a pressure difference arises between the inside of the construction cavity and the outside surfaces. However, if the construction cavity is not sealed, the pressure difference causes the cavity air to leak out of the cavity until the pressure difference is zero. Similarly if the barometric pressure rises, the opposite effect will occur. Air will leak into the construction cavity until the pressure within the cavity equals the barometric pressure.

A problem arises when the construction cavity leaks to the indoor side rather than the outdoor side. Normally in winter, one side of an insulated wall cavity is colder than the other. When the barometric pressure rises, it causes humid indoor air to enter the construction cavity and the moisture in the air may condense on the surface of the cold side of the cavity space. When the barometric pressure falls again, the construction cavity will expel a small amount of air from the cavity, leaving behind the small amount of moisture which has condensed on the cavity surfaces. When the pressure rises again, the cycle repeats and more moisture is transferred to the inside surfaces of the construction cavity the same way (*see* Figure 7).

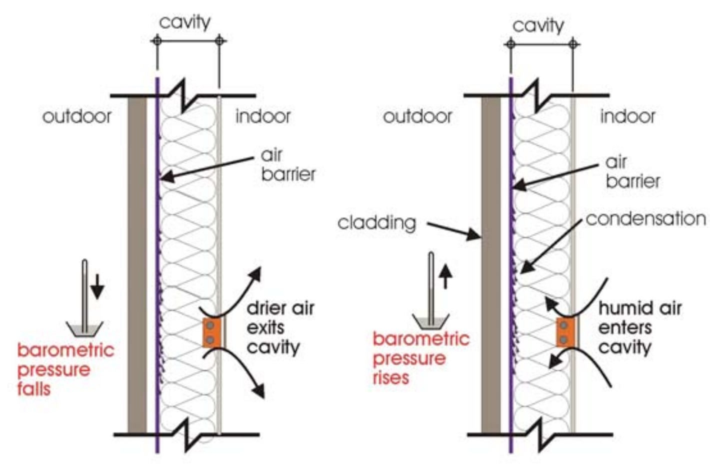


FIG.7 - BAROMETRIC CYCLING

This action occurs in all construction cavities that are not perfectly sealed and it has been observed in the field and measured in a laboratory. In an experiment designed to measure moisture entry into cavities,[4] it was found that barometric cycling caused the wetting of cavities about 10 times faster than by vapour diffusion alone. This does not mean that vapour retarders should also be air barriers. Rather, it indicates that unless the cavity is hermetically sealed, as in an insulating-glass unit, the direction of breathing for a cavity should favour drying rather than wetting. This means that the location of the air barrier may require further consideration.

Air exchange due to barometric cycling

Assuming an initial barometric pressure of 103 kPa, a drop in barometric pressure to 98 kPa could result in a pressure difference of 5 kPa. This is equivalent to 100 lb./ft^2. However, if an envelope cavity is not sealed and a leakage path leads to the indoor side, up to five per cent of the cavity air must exit the cavity to attain pressure equalization with the barometric pressure. While five per cent appears minuscule, if it occurs twice a day over two months, the cavity may experience up to six complete air changes with a proportional moisture load from condensation.

4 *Causes of condensation moisture in construction cavities*, an unpublished laboratory experiment examining stack effect, convection loops, diffusion and barometric pumping as sources of condensation moisture in wall cavities. This work was conducted by the author in the early 80s.

It has also been observed that micro changes in barometric pressure of only 50 Pa may occur up to 50 times an hour, the result of wind buffeting a building. A 50 Pa pressure cycle is only 0.05 per cent of the barometric pressure and therefore represents a change of only 0.05 per cent of the cavity air mass. But this change can result in a 2.5 per cent air change an hour or 60 per cent change of the cavity volume per day.

This phenomenon may cause a significant moisture transfer into wall cavities. It may require reconsideration of numerous building envelope applications, including the design of traditional flat roofs, architectural precast-clad exterior walls, double hung windows and various face-sealed cladding systems.

Consider a traditional flat roof built with a 4 ply BUR, 100 mm of fibrous insulation, a vapour retarder and a steel deck. If the insulation is 95 per cent void, then the cavity is about 95 per cent of 100 mm × the area of the roof.

The waterproof membrane forms one side of the cavity, and the vapour retarder (polyethylene sheet) the other side. As the BUR is a considerably more robust air barrier than a 4 mil, polyethylene-sheet vapour retarder, any change in cavity pressure would leak into or out of the roof cavity from inside of the building. In winter, this would result in condensation forming on the underside of the BUR membrane, eventually wetting of the roof insulation, particularly around roof drains that are not sealed to the vapour retarder. The condensation results from the barometrically pumped humid air into the roof cavity. Wet roof insulation is common, but it has yet to be attributed to causes other than simple roof leaks. Architects should consider that wet roof insulation may be attributed to causes other than roof leaks and air leakage-related condensation.

Barometric cycling is a phenomenon which is a relatively unknown to industry professionals. It can cause both wetting and drying of cavities, depending on the time of year, indoor conditions and the direction of the openings connecting to the cavity. If most of the openings lead to the exterior, the cavity will tend to dry out if wetted. If most of the openings to a cavity lead to the indoor side, the cavity will tend to become wet due to condensation in winter if it was previously dry. The amount of wetting or drying is also dependent on the cavity volume and the location of the openings leading to the cavity.

Preventing barometric cycling problems

To avoid wetting of cavities by barometric cycling, it is best to place the air barrier on the inboard side of the insulation so that any venting of cavities is to the outside of the insulation. If this is not practical, the air barrier may be placed between two layers of insulation so long as the air barrier remains on the warm side of the dew point temperature location.

Lastly, if the air barrier must be placed outside of the insulation, the cavity air volume needs to be reduced between the insulation and air barrier and /or a high vapour permeance air barrier material should be selected to allow barometrically trapped moisture to diffuse to the outside.

Temperature cycling effects

Another air pressure-induced problem for cavities occurs when the cavity air temperature changes or cycles over a wide temperature range. The widest range is usually from summer to winter and vice versa. However, a once-yearly cycle is insignificant to moisture-transfer in cavities.

A more significant condition occurs on a daily basis when a cavity temperature cycle is amplified by the sun. This occurs when one of the cavity surfaces is exposed to the sun's radiation and the temperature of the surface of the cavity increases above the outdoor air temperature. This is also referred to as *sol-air* temperature. For example, on a cold morning when the rising sun impinges on a dark cladding, the surface temperature of the cladding may increase from a few degrees below the ambient outdoor temperature to well above outdoor temperature conditions. This can be as much as a 40°C (104°F) difference from the cold of the night to the daytime high. In so doing, the cavity air also increases in temperature, sometimes by 20°C (68°F) or more. This increase in cavity temperature then causes the cavity air to expand.

If the construction cavity is hermetically sealed and cannot expand, the expansion will be converted to a pressure increase, causing a pressure difference on the panels that define the cavity. However, construction cavities are rarely perfectly sealed. The expansion of the cavity air will result in the leakage of a minute quantity of air from the cavity. As with barometric cycling, the direction of the leaks is most important. If the leaks lead to the indoor side, the cavity air will leak to and from the indoor environment.

Later when the sun no longer impinges on the cladding, the surface temperature cools down to the ambient outdoor temperature. At night this can mean a drop of 40°C (104°F) or more from the daytime high. It is this cooling cycle that causes the cavity air volume to contract slightly in the cavity. In turn, this air contraction draws indoor air into the construction cavity. If the indoor air is humid, the cavity may exhibit an increase in wetness particularly as the cycle repeats day after day during a winter period. (*see* Figure 8.)

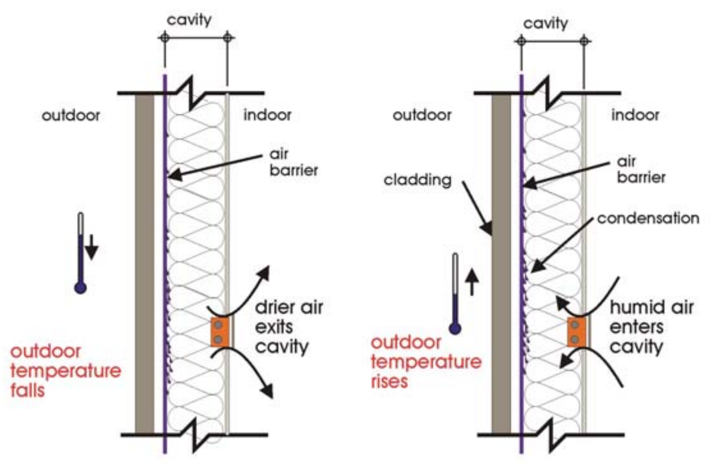


FIG.8 - TEMPERATURE CYCLING

Air exchange due to temperature cycling

To determine a measured amount of air leakage caused by a temperature change, the equation PV=nRT may be consulted. Although the correct analysis would involve a change in mass (mole fraction) of the gas, the volume expansion method which follows is simpler to visualize:

If $P_1V_1/T_1=P_2V_2/T_2$ and $V_2=V_1+\Delta V$ then $\Delta V=(T_2P_1V_1/T_1P_2)-V_1$.

where P_1 and P_2=absolute pressure, Pa

and V_1 and V_2=volume, m^3

and T_1 and T_2=temperature, °K

and ΔV=change in volume, m^3

Assume a unit cavity volume, V_1 equal to 1 m^3 and an absolute temperature T_1 of 263 (273-10)° K which is also equal to -10°C. If the sol-air temperature on the cladding rises from T_1 =263°K to reach T_2 =303 (273+30) °K, which is also equal to 30°C, while the pressure remains constant so that $P_1=P_2$, then the change in volume, ΔV of the cavity air would be, 0.15 m^3 or 15 per cent. In other words, 15 per cent of the cavity air is expelled. Similarly, if the cavity air is cooled at night, a measured amount of cavity air infiltration will occur, up to 15 per cent or more, depending on the amount of cooling. Once again, such an amount is minuscule in relation to the moisture input required to produce significant condensation if only one cycle occurs.

When moving clouds temporally block the sun, the sol-air temperature may change quickly to induce a several cycles of air exchange. Such changes have been noted in field measurements and can result in a mass cavity air change of up to one volume within seven or more cycles of heating and cooling. It is the extent of the temperature change and duration of each cycle that determines whether a significant amount of wetting or drying occurs during the winter season.

This cavity-heating phenomenon may occur in many types of construction cavities, but it is believed to be most significant in sloped and flat roofs, exterior walls with metal, plastic or thin cementitious cladding panels and cracked or damaged insulating glass units (IGU).

A cracked or leaky IGU is an example of this phenomenon at work. When the inner light is cracked, it would not be unusual for the sealed unit to partially fill with condensation. This happens because as the dry cavity air is heated by the sun, it expands and leaks out into the indoor space. When the cavity cools, humid indoor air leaks into the glass cavity to increase the cavity air moisture content. When the outside temperature drops below the dew point temperature of this air, visible water beads or streaks of condensation are formed on the inside surface of the outer glass pane, which then accumulate at the bottom of the sealed unit.

Alternately, if the crack in the IGU faces the outside, the cavity air will leak to the outside upon heating and outside air will leak into the cavity upon cooling. Because the outside air is dry, there is much less potential for condensation. Still the IGU unit will eventually become unusable due to dust accumulation and poor vision qualities.

Thermal cycling causes many envelope cavities to exhibit moisture problems in winter in the northern latitudes. In the southern latitudes, the phenomenon is reversed because it is the outdoor air which is hot and humid over prolonged periods, and which condenses in construction cavities. This phenomenon must be considered in the design of a quality building envelope because of the moisture problems it may engender. Similarly, thermal cycling may be used to advantage to dry out cavities if the vent openings are directed to the outside such as the rainscreen wall system and the inverted roof assembly.-

Designing for thermal cycling

The recommendations for thermal cycling are the similar to those for dealing with barometric cycling, except that in the case of thermal cycling, the sol-air temperature on surfaces may be reduced by the use of light colours, or more massive exterior cladding materials having greater heat storage capacity.

Dynamic Buffer Zone concept

Mechanical services are now commonly used to provide greater indoor humidity and to pressurize all public buildings. This practice also applies to existing buildings being retrofitted or upgraded and includes many heritage buildings. Unfortunately, it has been observed that most heritage buildings cannot support higher indoor humidity without extensive intervention to protect the existing wall construction, usually masonry, from moisture damage. Thus, it would be necessary to air-seal the exterior wall almost perfectly from the inside to prevent the transmission of indoor moisture into the old masonry wall by air leakage. Regrettably, progress in airtightening of building envelopes has not yet attained sufficient quality to limit the air leakage rate below that which would prevents moisture damage to heritage masonry walls.

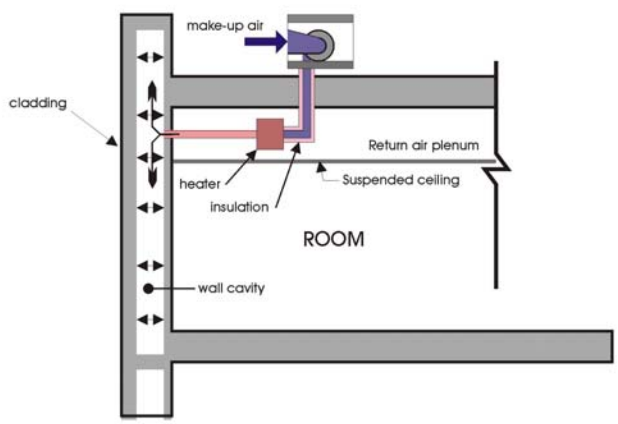
For this reason, another method to limit or prevent condensation in construction cavities, particularly those of heritage character, has been sought. The late Kirby

Garden, former researcher with the National Research Council of Canada, developed a strategy of ventilating construction cavities with partially heated air in order to prevent cavity condensation. While the method was used on a few occasions, it was only found to be effective in some applications.

In an effort to improve the original concept, the Dynamic Buffer Zone, or DBZ concept, was developed by the author, with the assistance of the late Michel Perrault, another building envelope consultant. In essence, the concept uses ventilation equipment to increase the ambient pressure in an exterior wall or roof cavity in order to reverse the pressure difference across the cavity closure, usually the indoor finish. In turn, the reversal of the pressure difference direction also reverses the flow of air leakage at minor openings, cracks and holes.

This method does not ventilate a cavity, it merely pressurizes it to above the indoor condition to prevent the exfiltration of indoor air through the cavity. This method was found to be considerably more effective than the original ventilation concept and half as expensive to implement (see Figure 9). It has been applied in more than 15 building projects in Canada in the last five years and found to be effective in all cases. Some of the projects include the Canada Life Building (older building) in Toronto, the East Memorial Building in Ottawa, the Alexandria Hospital in Edmonton and the Municipal Archive of Montreal to name a few.

FIG.9 - TYPICAL PRESSURE STYLE DYNAMIC BUFFER ZONE APPLICATION



Architecture and Engineering Services of Public Works and Government Services Canada (PWGSC), funded an applied research project into DBZ technology from1994-1996. In this project, it was determined that for many types of construction cavity exterior walls of masonry, a DBZ system need only supply between 14 and 24 l/s (30 and 50 cfm) of air per 9.3 m^2 (100 $ft.^2$) of exterior wall. If the DBZ cavity to be pressurized is outside the insulation layer, the outdoor air need only be pre-heated by about 10°C above the outdoor temperature. If the DBZ cavity is on the warm side of the insulation, the DBZ air need only be heated to about 5°C below the indoor ambient temperature. Fan power need not exceed a capacity of 0.5 inch H_2O pressure at stagnation. This is the maximum required pressure difference of the DBZ fan pressurization system for most applications. However, due to the variations in wall cavity airtightness, the pressurizing fan must be equipped with a variable speed controller.

In most places in Canada, the DBZ should be operated continuously from about Oct. 15 to about May 15. The PWGSC study observed that energy costs were negligible to none, when energy savings from reduced leakage losses are included in the benefits. The DBZ is not operated in summer regardless of whether the building is air-conditioned or not.

The application of the DBZ pressurization concept requires a space or cavity within a roof or exterior wall into which pre-heated outdoor air can be injected to pressurize them. In this approach, the pressurized wall cavity need not be perfectly sealed, but the largest holes on the inside finishes must be sealed. Any hole larger than a pencil-diameter opening should be covered or sealed. Also, the cavity does not need to be perfectly open or clear because the DBZ pressurization does not require flow-resistance consideration and no return or exhaust ducts are required from the cavity. Most important, all cladding drain and vent openings to the outside must be closed and sealed.

A DBZ system is pressure-controlled only. Outdoor air is supplied into the DBZ cavity until the cavity pressure rises to between 5 and 10 Pa above the indoor ambient building pressure or until the fan operates at its upper limit. Thus, no matter the pressure of stack effect in the building, the fan control system maintains adequate air pressure in the cavity. It is the higher cavity pressure which prevents indoor humid air from entering the exterior wall cavity and prevents cavity condensation problems.

Another benefit of the DBZ concept is that if a masonry wall is wetted by a prolonged rain, the operating DBZ dries out the cavity in less than 48 hours after the rain.

When to use a DBZ system

A PWGSC DBZ study at the West Memorial Building, Ottawa found that the DBZ pressure-style application is more effective than the best-possible air barrier system that could otherwise be constructed for heritage buildings with raised indoor humidity in a cold climate. This is because the reversed pressure difference prevents any indoor air from leaking into the cavity as if it were a perfect air barrier and it is forgiving of minor design errors or omissions, and poor construction. Further, it is less expensive to implement than an air barrier retrofit of equal effectiveness, by 50 per cent or less. The only time that the DBZ system did not perform was when the system was shut down for maintenance or repair. In simple terms, a DBZ system acts as a virtually perfect air barrier. It is a pressurization system used to counteract the pressurization results of stack effect and ventilation pressure variations.

- Air barrier retrofit for heritage buildings is intrusive and rarely effective when the building is humidified and pressurized. When a heritage building is to be humidified and pressurized, it is recommended that a DBZ system be considered in the upgrading of the building envelope.

- The DBZ concept could also be considered for new buildings requiring increased and controlled indoor humidity conditions. These could include hospitals, museums and high humidity industrial buildings.
- The DBZ concept may be applied to parts of the building envelope such as the roof alone or one side of the exterior walls if required. For example, it may be applied to parapets uniquely or to grade level soffits, column and spandrel covers and other limited applications.
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Conclusions and recommendations

The application of science and technology to building envelope design continues to expand. In previous research and publications, many issues have been considered:

- condensation by diffusion control through the use vapour retarders
- condensation by air leakage control and air barriers,
- energy conservation by heat loss control with insulation
- rain penetration control with the application of the rainscreen principle.

There remains an important consideration of equal, if not more importance, than those noted above—air pressure and control of air pressure difference. It was always important in wind design, but now it must be extended to the architectural design of the building envelope if the performance and durability of the building envelope are to continue to improve. It is also important to understand these phenomena if the application is to be properly designed, and if new and more cost-effective ways of attaining higher quality building envelopes are to be found. In summary, the following conclusions and recommendations are submitted for consideration:

1. Pressure cycling and air pressure difference must be considered in building envelope design.
2. To better understand the effects of barometric and temperature cycling, it is recommended that the simple calculation models presented here be applied to moisture simulation models to assist designer in predicting the significance of the phenomenon in various applications. It is not necessary for a designer to become proficient in the above noted calculations. But the designer should be aware of the modelling required if an estimate of moisture accumulation is needed.
3. In general, buildings in the Canadian climate should have all construction cavities breathing to the outside wherever possible.
4. Fan pressurization recommendations by ASHRAE should be reviewed as soon as possible. The current ASHRAE ventilation design recommendations for building pressure may induce unnecessary building envelope moisture problems.
5. The design of air barriers is not yet fully understood at the architectural level. It cannot be over-emphasized that air barriers must first be designed structurally to withstand peak and sustained pressure loads. Then the air barrier system must not leak in excess of the stipulated maximums of the applicable building code.

6. Stack effect cannot be overcome. The control of air leakage caused by stack effect in high-rise buildings is inadequate. If indoor air is even modestly humidified, there will be moisture and condensation problems in the building envelope. It is recommended that further research be undertaken into improved building envelope design and air barrier design in particular.

Barometric pressure and temperature cycling of building envelope cavities is generally unknown and poorly understood. While the fundamental physics is well developed, the application needs further research to reduce the damage of condensation moisture in buildings.

References

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Questions

1. List four of the most typical problems caused by the pressure of stack effect in a medium rise building?
2. If the indoor temperature is 22°C and the outdoor temperature is -15°C, what is the stack effect pressure at the roof and at grade of a 24-m, eight-storey building, with a neutral plane at 5 m above grade?
3. What is an indoor pressure coefficient in terms of wind pressure design?
4. What is the stagnation pressure of an 80 kmh wind?
5. Of what importance is design wind pressure in air barrier design?
6. What is the barometric pressure at an altitude of 5 km above sea level?
7. When the barometric pressure is rising, does air leave or enter a cavity?
8. In a cold climate, where should the air barrier be positioned to minimize the negative effects of barometric pumping?
9. What is a cause of frequent temperature cycling?
10. To minimize the effects of temperature cycling in roof cavities, is it better to specify a traditional roof system or an inverted roof membrane assembly?
11. What are the two styles of cavity ventilation systems by fan operation?
12. What parameter is used to control the fan speed of a DBZ system?