The Impact of Airtightness On System Design

By Wagdy A.Y. Anis, AIA

It is commonly believed that infiltration is due to poorly weather-stripped doors and windows. Although this is partly true, the fact is 80% or more of infiltration is due to the many imperfections that are designed or built into exterior envelopes. "Will we have enough fresh air to breathe?" is a concern about air-tightening the envelope. ANSI/ASHRAE Standard 62-1999, *Ventilation for Acceptable Indoor Air Quality* has taken care of that problem. Doesn't air tightening cause sick buildings? To quote, Joseph Lstiburek, Ph.D., P.Eng., Member ASHRAE,[1] "in order to control air, you must first contain it."

Air pressure acting on building envelopes can wreak havoc with building performance if not properly understood and adequately designed for. Uncontrolled air pressure across the building envelope and within the building itself can cause infiltration and exfiltration that overpower HVAC systems. By disrupting the HVAC design, pressures can cause discomfort and create infection control and indoor air quality problems.

In heating climates, exfiltrating air carries with it water vapor and lost energy. The water vapor condenses and causes many problems, from wetting to bacterial growth and deterioration of the building envelope.

In cooling climates, water vapor is carried in with the infiltrating air, causing condensation, mold, and bacterial growth. Moisture-laden air can travel within interstitial spaces due to negative pressures inside those spaces. The moisture can condense in strange places like interior walls and ceilings that are connected to the building envelope.

Leakage Characteristics[2]

Air leakage can occur through pores in materials, cracks, holes, or other openings. Flow is produced by a pressure difference that provides the energy to overcome friction and other losses. Air leakage transfers heat, water vapor, smoke, odors, dust, and other pollutants, either from outdoors into the building or from sources within the building.

Airflow characteristics vary according to the size and shape of the opening. Long paths with small cross-sections may exhibit laminar flow and have resistance proportional to velocity. Larger holes may act like orifices with resistance to flow varying with the square of velocity. Usually, different kinds of openings contribute to the total leakage. It is not practical to identify, measure, or calculate each individually. Overall flow rates for the aggregate of openings take the form:

$$Q = C(\Delta p)^n \qquad (1)$$

where

Q = volume flow rate, cfm
C = Flow coefficient, cfm/(in. w.g.)^n
Δp = Pressure difference
n = an exponent ranging between 0.5 and 1.0. An exponent of 0.65 represents many cases of wall and window leakage.

Figure 1 illustrates the relationship between pressure difference and flow through building openings.

Three major sources of air pressure on buildings are wind pressure, stack pressure, and HVAC fan pressure. Two minor pressures are changing barometric air pressure and temperature differentials across the building envelope. They are inconsequential relative to the three major pressures.

Air Leakage From Wind Pressure

Although peak pressures are important for structural calculations, mean values are more appropriate for computing infiltration rates. Time-averaged surface pressures are proportional to the wind velocity given by Bernoulli's equation, as follows:

$$p_v = \frac{\rho_a U_H^2}{2g} \qquad (2)$$

where

p_v = surface pressure, lb/ft^2

About the Author
Wagdy Anis, AIA, is a principal and director of Technical Resources at Shepley Bulfinch Richardson and Abbott, Boston.

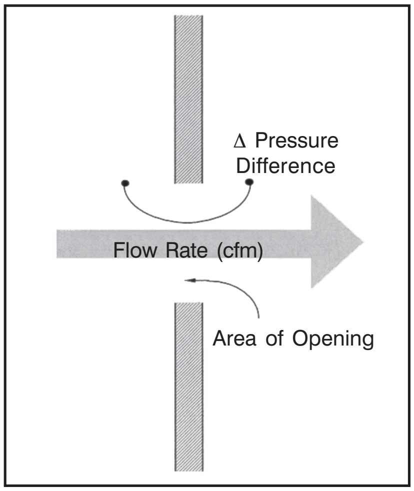

Figure 1: Airflow rate is determined by the size of the hole and the pressure difference.

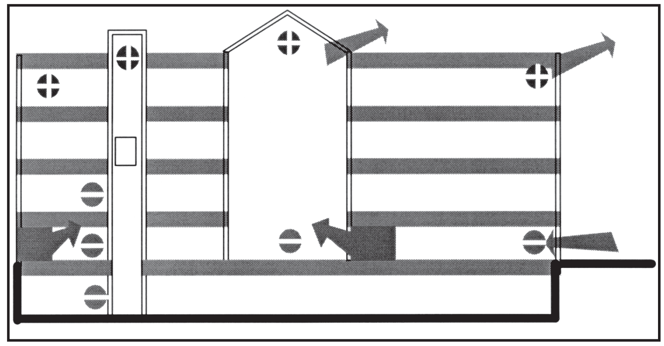

Figure 2: Stack effect.

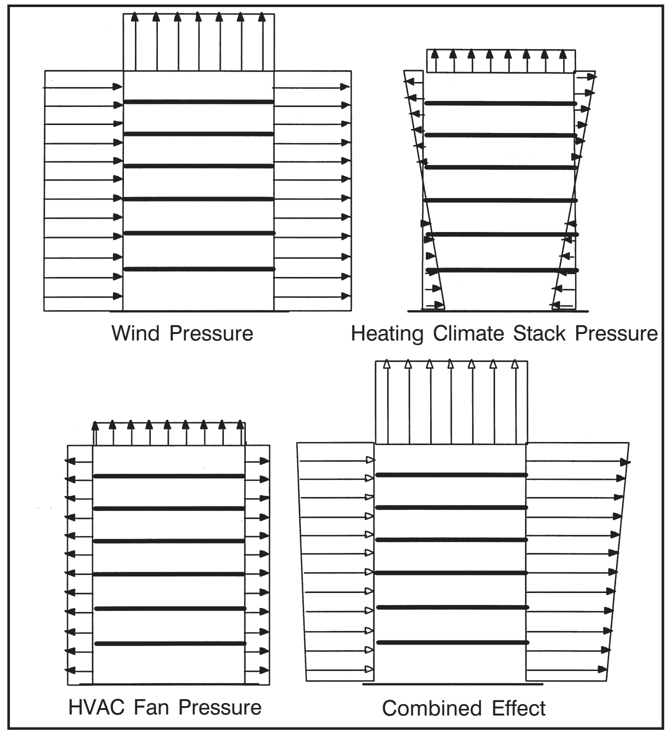

Figure 3: Combined wind, stack and fan pressure.

U_H = approach wind speed at upwind wall height H, ft/s
ρ_a = outdoor air density, lb/ft^3
g = gravitational acceleration, ft/s^2

The difference between pressure on the envelope surface and local outdoor atmospheric pressure at the same level in an undisturbed wind approaching the building is given by

$$p_s = C_p \cdot p_v \tag{3}$$

where
p_s = difference in pressure, lb/ft^2
C_p = local wind pressure coefficient (depends on terrain).

Of the three major air pressures, wind is usually the greatest. If the wind hits the building broadside, air infiltrates on the windward side and exfiltrates on the other three sides and through the roof. If the wind hits at an angle, it positively pressurizes two sides, and air exfiltrates on the two leeward sides and through the roof.

Infiltrating air is unconditioned for temperature and moisture content and can contain pollutants. It causes discomfort and can cause imbalances in spaces such as patient isolation rooms, protected environment rooms, or chemical storage areas that are designed for controlled pressure, thus compromising pollutant control.

Chapters 16 and 26 of the *2001 ASHRAE Handbook—Fundamentals* quantify wind pressures on buildings and their effects on mechanical systems.

Stack Effect

Have you ever approached the front door of a building in winter and found the door really difficult to pull open, and then it opened with a "whoosh?" This condition is due to stack effect. Stack effect or "chimney effect" in buildings is caused by the difference in weight of the column of conditioned air inside the building versus the air outside the building. This difference in weight creates a pressure difference across the building envelope.

Absolute air pressure changes more rapidly with height outdoors than indoors, causing the pressure differential. Mechanical and elevator shafts, stairs, and atria connect the bottom of the building to the top and transfer the stack pressure at each floor to the envelope. *Figure 2* illustrates stack effect.

The taller the building, the higher the stack pressure. In heating climates, air exfiltrates at the top and is replaced by air infiltrating at the bottom of the building. In cooling climates, the opposite occurs. Cold air coming in can cause discomfort at the lower floors and overpower the heating system. In a 40-story building, with a 13 ft (4 m) story height, temperatures of 20°F (–7°C) outdoors and 70°F (21°C) indoors, and assuming openings of equal area at the top and bottom of the building, the infiltration stack pressure at street level (and exfiltration at the top of the building) is 0.4 in. w.g. (100 Pa).

The design of garage exhaust systems needs to account for stack pressure in the building above. Stack pressure can exceed exhaust fan static pressure. If it does, a garage under a building can be a source of pollutants that are sucked into the building. A good passive solution to the problem would be to use vestibules and door weather stripping to isolate and compartmentalize the garage from the building above at stairs, elevator shafts, and other physical connections that allow this stack pressure to connect the building to the garage. Compartmentalizing the building horizontally into individual stories or small groups of a few stories and disconnecting them from the shafts fools the building into acting like a stack of single-story or low-rise buildings, thereby reducing stack effect.

Outside air and exhaust fans in multistory apartment buildings often are not selected to account for stack pressure. Multistory systems with vertical ducts or shafts, such as bathroom exhaust systems in hotels, have been known to fail miserably, with the bathroom exhaust from lower floors being sucked into the bathrooms at the upper stories of the building. If passive compartmentalization is not part of the design, individual systems that serve each floor might be necessary to overcome stack effect. Controls that include pressure sensors and variable speed drives then can adjust fan speed to account for changing pressures on the envelope. Supply systems with vertical duct distribution shafts have to work against varying pressures during the year. There seems to be no easy solution that allows the original balancing to work reliably at all times.

Have you ever noticed how some brick buildings will turn whitish with efflorescence at the top parapet? That is due to air escaping at the juncture of the top floor's walls and roof. Moisture in the exfiltrating air condenses on the back or within the brick, dissolving salts from the masonry. The moisture dries at the surface of the brick, leaving salts on the surface. In the spring, rain dissolves the salts again and the whitish stain disappears.

Besides efflorescence, moist air exfiltrating at the top of the building can cause damage by decay and corrosion, spalling of masonry and stone, and bacterial growth. Inter-floor pressure differentials can also disrupt designs sensitive to accurate pressure relationships in non-compartmentalized buildings.

Stack pressure is quantified at height H as:

$$\Delta_{ps} = C_2(\rho_o - \rho_i)g(H - H_{NPL}) = C_2\rho_i g(H - H_{NPL})(T_i - T_o)/T_o \quad (4)$$

where

Δ_{ps} = Pressure due to stack effect, in. w.g.
ρ = air density, lb_m/ft^3
g = gravitational constant, 32.2 ft/s^2
H = height of observation, ft
H_{NPL} = height of neutral pressure level, ft
T = average absolute temperature, °R
C_2 = unit conversion factor = 0.00598.
Subscripts,
$_i$ = indoors
$_o$ = outdoors.

The neutral pressure level is the elevation where airflow changes from exfiltration to infiltration. In buildings with equal leakage area at the top and the bottom of the building, the neutral pressure level occurs at mid-height of the building. The location of the neutral plane is affected by the relative area of leakage at the top versus the bottom of the building. In most buildings, more leakage happens at the top, due to louvers in mechanical rooms, elevator shaft open smoke vent louvers, even weep holes in skylight curbs, and especially the wall-to roof connection, which most architects do not attempt to design to be airtight.

The following equation can be used to combine wind and stack infiltration:

$$Q_{ws} = \sqrt{Q_W{}^2 + Q_S{}^2} \quad (5)$$

where

Q_{ws} = combined infiltration airflow, cfm
Q_w = infiltration airflow from wind, cfm
Q_s = infiltration airflow due to stack effect, cfm.

Building Type (No. in Sample)	Mean Normalized Leakage Rate cfm/ft² at 0.3 in. w.g. (L/s·m² at 75 Pa)		
	Type 1 Data	Type 2 Data	Type 3 Data
Multi Unit Residence Buildings			
Canada (12)	0.628 (3.19)		
Canada (3)		0.787 (4.00)	
Canada (6)			0.636 (3.23)
Office Buildings			
Canada (8)	0.488 (2.48)		
U.S. (7)	1.163 (5.91)		
Great Britain (12)	1.486 (7.55)		
Great Britain (13)		1.313 (6.67)	
Schools			
Canada (11)	0.291 (1.48)		
U.S. (14)	0.480 (2.44)		
Commercial			
Canada (8)	0.266 (1.35)		
U.S. (68)	1.217 (6.18)		
Canada (10)		2.746 (13.95)	
Industrial			
Great Britain (5)	1.368 (6.95)		
Great Britain (2)		4.433 (22.52)	
Sweden (9)		0.285 (1.45)	
Institutional			
Canada (2)		0.169 (0.86)	

Type 1 Data: Test performed on whole building; total envelope area (including below grade) used to calculate NLR at 0.3 in. w.g. (75 Pa)
Type 2 Data: Test performed on whole building using different test pressures; Data converted to NLR at 0.3 in. w.g. (75 Pa).
Type 3 Data: Test performed on individual floors or suites; Exterior wall area of floors or suites used to calculate NLR at 0.3 in. w.g. (75 Pa).

Table 1: Mean Normalized Leakage Rate (NLR) at 0.3 in. w.g. (L/s·m² at 75 Pa) by building type and data type.

Fan Pressure

HVAC engineers often design buildings to be under a net positive pressure. This reportedly helps keep pollutants and untreated air out of the building. The uncertainties of infiltration through the envelope may drive this common practice. The results are hit or miss. Recent studies and testing on whole building air leakage are summarized in *Table 1*. Air leakage rates due to infiltration are all over the place.[3]

In heating-dominated climates, net positive fan pressure has the effect of driving moisture-laden air through the many unavoidable imperfections that are built into walls, floors and roofs. Water condenses in the winter, damaging the envelope. From an envelope durability standpoint, buildings should be pressurized slightly negative in heating climates and positive in cooling climates. What is practical from an HVAC performance standpoint is sometimes inconsistent with the durability needs of the envelope.

Fan pressure is caused by design or by accident. One four-story academic laboratory building the author recently reviewed in the winter was running under a negative pressure of 0.3 in. w.g. (75 Pa) on the second floor. When it rained, water was sucked into every crevice in the envelope. The building leaked like a sieve, aided by less than adequate flashings. The HVAC system could not deal with all the infiltration, and people were cold. The negative pressure was caused primarily by an inadequate balance between the supply and exhaust.

Figure 3 illustrates the combined influence of stack effect, wind pressure, and fan pressure.

Recommendations

So what is the answer? Prudent building envelope design will take air pressures into consideration. An airtight building envelope is crucial to proper HVAC system function. Horizontal compartmentalization of the floors and isolation from shafts is essential to control stack effect and the spread of smoke and fire. Air barrier design technology is essential to success. Designers can take the following actions:

1. Design the exterior envelope and all its components to withstand the combined design wind, stack, and fan pressures in an airtight manner. Massachusetts, funded by U.S. Department of Energy (DOE) and the utilities, is providing free envelope energy code training including design guidance on air barrier technology and educational details.[4] Specifications for air barriers systems are available from the Air Barrier Association of America (ABAA)[5] as well as details of its Quality Assurance Program, qualified contractors, etc.

2. Design an air barrier system into the building envelope that can take this pressure, both positive and negative, without displacement or failure. This will help control air infiltration and exfiltration. For areas within a building with significantly different climates, include an air barrier system into the separation between the two areas, such as between pools and offices, or humidity-controlled areas and adjacent uncontrolled areas.

3. Separate shafts (elevators, stairs, ducts and atria) from the floors they serve by airtight assemblies. Provide vestibules and gasket doors and access panels to control transfer of stack pressure.

Water Vapor Permeance (WVP) of Outermost Layer of Wall Assembly perms (ng/Pa·s·m^2)	Maximum Permissible Air Leakage Rates cfm/ft^2 at 0.3 in. w.g. (L/s·m^2 at 75 Pa)
0.25 (15) < WVP = 1 (60)	0.01 (0.05)
1 (60) < WVP = 3 (170)	0.02 (0.1)
3 (170) < WVP = 14 (800)	0.03 (0.15)
> 14 (800)	0.04 (0.2)

Table 2: Allowable leakage rates.

4. Separate pollutant areas such as photocopy rooms, chemical or cleaning storage areas, toilets, and garages with gasketed doors, and make the surrounding partitions airtight at the deck and floor.

Code Requirements

When Standard 90.1 was updated for release in 1999, the drafters recognized that an opportunity was being missed. Section 5.2.3, Air Leakage, notes: "It is difficult to specify in great detail the ways to limit air leakage, which is unfortunate given its potential significance. Minimizing air leakage is important to maintaining comfort, enabling the mechanical system to meet loads, and maintaining building pressurization in case of a fire, in addition to the benefits of reduced energy bills."

So we continue with energy code requirements, including ANSI/ASHRAE/IESNA Standard 90.1-1999, *Energy Standard for Buildings Except Low-Rise Residential Buildings* and The International Energy Conservation Code (IECC 2000), which are extremely vague when it comes to air tightening the building envelope. Air tightening is typically called for by requiring caulking, gasketing, weather stripping and stuffing crevices and cracks. That is an outdated and naïve approach to a major problem in buildings today.

With energy sources becoming problematic worldwide, it is an unsustainable position. The *2001 ASHRAE Handbook—Fundamentals*, Chapters 23 and 24, clearly calls for the solution, requiring building envelopes to be designed with an air retarder or barrier. *The Envelope Design Guidelines for Federal Office Buildings: Thermal Integrity and Airtightness*[6] also contains clear details and requirements for air barriers. The Building Environment and Thermal Envelope Council (BETEC), division of the National Institute for Building Sciences has held three symposia, Air Barriers I, II and III, from 1999-2001, sponsored by DOE and Oak Ridge National Laboratory (ORNL), to draw national attention to the problem of air leakage in buildings and how to take care of it using air barrier technology. The promoted technology continues to be ignored in the codes and therefore, in actual practice. It is the author's belief that until air barriers are clearly required by code, it will be business as usual in designing and building buildings that leak air.

An "air retarder" or "air barrier" is a component of the building envelope that the designer selects in each envelope system to be airtight. It is taped or otherwise made airtight. It has to be structurally supported to withstand the positive and negative pressures on the envelope. It is joined with the air barrier component of the adjacent system in a flexible and airtight manner, using membranes, sealants, etc. The National Building Code of Canada (NBC) has had these requirements for 16 years. Section 5.4.1, Air Barrier Systems, of NBC 1995 requires a minimum air barrier material airtightness of 0.02 L/s·m^2 at 75 Pa (the airtightness of a sheet of 0.5 in. (12.5 mm) unpainted gypsum board).

Earlier this year, Massachusetts adopted a new energy code. Section 1304.3.1, Air Barriers, imposes a clear requirement for air barriers in the exterior envelope. The requirement is similar to the Canadian Code and has the same value of airtightness for materials that qualify as an air barrier (0.004 cfm at 1.57/ft^2 or 0.3 in. w.g. [75 Pa]). Massachusetts opted not to define "airtight" since airtightness is relative, and the building and design industries in Massachusetts are new to the concepts.

Air barrier materials of all envelope systems must be connected in an airtight and flexible manner, windows and doors to walls, walls to the roof and foundations, and all penetrations of the air barrier made airtight. The end result is a building with far reduced air leakage and more durable, energy efficient and healthier environment.

The Canadian Building Materials Centre has developed a testing protocol for air barrier "systems." A "system" is a wall connected to a foundation with penetrations such as conduits, a window, etc. The system is then tested under certain pressures and for varying lengths of time. The appendix to the Canadian Building Code suggests that the airtightness of the building envelope can be more or less relaxed depending on the interior humidity levels. The numbers relate to the air leakage of the air barrier "system." This does not relate to the leakage that can happen at significant flaws built into the building envelope. It envisions diffuse air leakage. From the point of view of the integrity of the envelope, it does not make sense to average out significant flaws over a large area or over the whole building. From the point of view of the HVAC design engineer, perhaps, but not necessarily.

There is an ongoing international debate as to what may, or may not be achievable in whole building airtightness. As seen in *Table 1*, which includes some Canadian buildings that were intentionally designed with air barriers under the C2000 program, the numbers in the Canadian code Appendix (0.02 cfm/ft^2 at 0.3 in. w.g. [0.10 L/s·m^2 at 75 Pa] for interior RH between 27% – 55%) were not achieved. Recent modeling[7] done in collaboration between NRC and VTT Finland refutes the maximum air leakage rates listed in the appendix of the NBC 1995 that are linked to the interior relative humidity. The newer recommendations[8] are to link the allowable air leakage rates of an air barrier "system" to the permeability of the exterior cladding. *Table 2* presents these recommendations. The modeling was done with an interior winter RH of 35%.

Until the dust settles and whole building testing becomes more readily available and meaningful (concentrated flaws create concentrated problems) the question will remain whether quantifying whole building airtightness is meaningful from an envelope design perspective. Certainly for the HVAC engineer, the ability to predict the building's airtightness is important from a design standpoint. Deliberately designing and building envelopes with care and with a target of airtightness is the best goal.

Where does the architect start and the engineer stop in building envelope design? A colleague, Fred Wacjs, Member ASHRAE,[9] tells me (partly because it's true and partly because I am an architect) that the building envelope is part of the mechanical system. The building envelope is designed by architects who, most of the time, do not realize the interaction between the envelope and the mechanical system. It is then built by many contracting trades to what they think is required by the design, without particular concern for airtightness. For this reason, more education and knowledge in this area is needed, and an informed collaboration is essential between all, particularly when the desired result is the air tightening of the building envelope.

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