Ventilation and Air Leakage

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Abstract:

Buildings leak water and air, which is normal and unavoidable. Therefore, designers should not fixate on preventing leakage, i.e. making buildings "airtight." Because even if all cracks were sealed, buildings have doors and windows.

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Buildings leak water and air, which is normal and unavoidable. Therefore, designers should not fixate on preventing leakage, i.e., making buildings "airtight." Because even if all cracks were sealed, buildings have doors and windows.

Instead, the designer's goal should be to A) quantify leakage, B) reduce leakage if excessive, and C) control leakage by managing air pressures with the HVAC system. "Designer" in this case means at least two people—the architect and the HVAC engineer. It also may include the builder and building official. Until the building science engineer evolves as a separate discipline, primary responsibility for addressing building leakage will probably fall to the HVAC engineer.

A bicycle tire needs to hold air long enough to complete a journey in reasonable comfort, and lose no more air than can be replaced by the pump at hand. Although appearing airtight, the tire eventually will go flat. We should expect the same performance from the air barriers that help to form a building's pressure envelope.

So how much leakage is acceptable? The author suggests as a modest goal that buildings should leak no more than the air that must be introduced for acceptable indoor air quality.

The amount of outside air (OA) mandated by ANSI/ASHRAE Standard 62, *Ventilation for Acceptable Indoor Air Quality,* is enough of a burden to the owner in terms of capital equipment cost and energy consumption. The owner should not need to provide even more OA to gain control of the indoor/outdoor pressure relationship.

Building Pressurization

Building air pressure with respect to outdoors should be neutral so that doors open and flue-gas vents function properly. However, should buildings be slightly positive or slightly negative? Most building scientists and mold remediation professionals now believe that wall and roof constructs should be pressurized from the cooler, dryer side. Dry air (with respect to the negative side) migrating through the wall absorbs moisture and tends to dry out the interstitial construction. Conversely, if hot, humid air is allowed to migrate through the construct, it can cool below its dew point and create condensation in the interstitial space, damaging building materials and allowing mold to grow.

With this principle in mind, buildings experiencing hot, humid weather should be positive with respect to the outside, and buildings in cold climates can be slightly negative. Experience has shown that designing for a very small pressure differential, (less than 0.01 in. w.c. [2.5 Pa] works well in hot, humid climates.

Wind currents will override pressurization this small. However, as wind shifts direction, it tends to cancel out its effects upon pressurization. This does not hold where one strong, wind direction prevails, such as by the sea. Cold climates will require a greater pressure differential, primarily due to stack effect.

"Leakage" is the natural, unplanned and uncontrolled flow of air into (infiltration) and out of (exfiltration) buildings. The artificial, intentional, controlled (hopefully) flow of air into buildings is called ventilation or outside air; the corresponding outward flow is exhaust. These intentional flows must work in concert with natural leakage.

The relationship between OA, exhaust, and leakage can be expressed with simple arithmetic:

Building Positive, Hot, Humid Climate:

$$\text{Outside Air} = \text{Exhaust} + \text{Leakage (Exfiltration)}$$

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$$1.0 \text{ ACH cfm} = V/60$$

Then, based upon the practitioner's experience, estimate an infiltration rate in terms of a fraction of ACH. The author, for example, has allowed between 0.50 and 1.0 ACH for "infiltration" throughout his career with reasonable success. Post-1973 buildings built to ANSI/ASHRAE/IESNA Standard 90.1, *Energy Standard for Buildings Except Low-Rise Residential Buildings,* requirements might be as tight as 0.25 ACH. Antiquated factory buildings on the other hand could experience 2 or more ACH.

Why did I use between 0.50 and 1 ACH? Because my HVAC professor at Iowa State told me to in 1962. All I had to go on was his direction, *Manual J*, and one tattered ASHRAE Handbook shared by the entire class. I had no need to question my assumption until 25 years later, when I was unable to heat a factory in Fargo, N.D., which had fenestration that had not been fixed for the past 55 years — its air apparently changed three times each hour. A few years later, I found that I couldn't dehumidify buildings in southwest Florida. I suspected there had to be better ways to estimate building leakage. There were.

Air change rates (ACH) continue to be a good way to express building leakage, but coupled with a pressure differential, normally 0.20 in. w.c. (50 Pa). A building would never operate (intentionally) at this pressure, but they can be more accurately tested at this high pressure (for the same reason that a damper or valve must experience a high-pressure differential before it can provide close control). The ACH rate at 0.20 in. w.c. (50 Pa) is interpolated to the actual building pressure desired (say 0.01 in. w.g. [2.5 Pa]) to determine how much air will be required for pressurization. The astute HVAC engineer should begin to see a relationship that looks like a constant mechanical duct system whose behavior can be predicted by

Building Negative, Cold Climate:

Outside Air = Exhaust – Leakage (Infiltration)

HVAC engineers can readily calculate how much outside air is required for acceptable ventilation as prescribed in Standard 62, and how much exhaust is required for toilets, showers, hoods, etc.

Building leakage is a bit more elusive. The goal of this article is to discuss the methods for measuring and expressing leakage, and to report the results of a case study, San Carlos Park Elementary School, in Ft. Myers, Fla.

Quantifying and Expressing Leakage

Perhaps the oldest (and worst) method for estimating building leakage was the "crackage" method, where the width of cracks around windows and doors was estimated, a cfm per linear foot of crack allowance assumed, and infiltration estimated by extending these computations.

A better (and certainly much easier) method is to begin by computing the volume of a building in ft^3 and then divide that number by 60 as an expression of the cfm airflow required to "change" the air in an hour's time (ACH):

the affinity laws. But read on — that will turn out to be only partly true.

Two expressions frequently seen in the literature to express the airtightness of a building are:

ACH50 – The number of times per hour that building volume will be replaced due to leakage at a pressure differential of 0.2 in. w.c. (50 Pa).

CFM50 – Leakage rate expressed in ft^3 per minute (cfm) at a pressure differential of 0.2 in. w.c. (50 Pa).

Another way to express leakage is to convert to one, equivalent size hole in the building. This procedure can be found in Chapter 26 of *ASHRAE Handbook—Fundamentals*.

The question then becomes, how do we determine what the leakage rate is for a particular building? Some possibilities are:

• Accepting whatever allowance for "infiltration" that has been built into cooling load software, according to an algorithm unknown to the engineer (not a recommended practice);

• An estimate based upon the designer's experience with similar construction;

• Searching out the results of other engineers' and scientists' work; and

• Actually measuring the building's leakage rate. This obviously would be limited to existing buildings, and to measuring the performance of newly constructed buildings.

Methods for Measuring Building Air Leakage

The most straightforward way to estimate a building's leakage is to place it under a test pressure, say 0.2 in. w.c. (50 Pa), and then measure how much air is required to accomplish this. It may be possible to configure part of the HVAC air-handling system to conduct such a test. A better procedure would be to run a blower door test.

In a blower door test, calibrated fans are installed in a building's exterior door openings, and the building is gradually evacuated down to 0.2 in. w.c. (50 Pa), with incremental pressures and airflows noted at intervals of approximately 0.02 in. w.c. (5 Pa). The incremental readings are necessary because buildings don't follow the exact same system curve as air ducts. Not only do different buildings leak at different rates, they follow differently shaped system curves, which we will examine later.

The micromanometer used for these readings must be capable of accurate readings to the nearest 0.0004 in. w.c. (0.1 Pa).

Depending upon the size of the building, how tight it is, and the capacity of the test equipment, it may not be possible to evacuate it down to 0.2 in. w.c. (50 Pa), a deep vacuum. In that case, the test must be suspended wherever the fans max out, and the ACH rate at 0.2 in. w.c. (50 Pa) extrapolated.

The test generally is valid with the building either in a vacuum or positively pressurized. A vacuum is usually preferred to keep suspended ceiling tiles seated. However, where the envelope is very tight, some leaks will act like check valves and could impact test results.

Testing leakage on a large building may require several resi-dential-sized blower doors operating in parallel. Or, the building could be (de)pressurized with its own air-handling system and accurate measurements made using standard testing, adjusting, and balancing techniques.

Intentional apertures in the building envelope placed there as part of the HVAC system act just like any other fault with respect to leakage, i.e., they are "holes." As a general rule during the blower door test, openings that would be dormant and open during normal building operation are left open. An intermittent toilet exhaust fan discharge would be an example. Openings that will be used during normal operation, such as an outside air intake, would be masked off and not considered as part of the building air leakage envelope.

San Carlos Park — Before and After Remediation

Pursuant to an overall HVAC and IAQ upgrade, the local school board requested that we make recommendations regarding the suitability of the building envelope at San Carlos Park Elementary School in Fort Myers, Fla. This 84,000 ft^2 (7800 m^2) building was approximately 20 years old and constructed from a steel frame, bar joists and steel deck roof, and masonry curtain walls. The quality of construction and condition of the building shell generally was good.

With an average height of 9.36 ft (2.9 m), 1 ACH calculated to 13,020 cfm (6144 L/s). 1,080 students, teachers, and other staff normally occupy the building.

One characteristic of the building concerned us. Florida schools require extensive overhangs to protect against intense sun and frequent rain. The exterior curtain walls rose only to the ceiling line and soffit of the exterior walkways (they were at the same elevation, about 9 ft [2.8 m] above grade). The ceiling return air plenum extended out over the exterior soffit and fascia area, which were not intentionally vented but covered with what appeared to be loose-fitting aluminum siding. It was all one, common space.

As part of the return air system, the overhang area was inherently the lowest-pressure zone of the building (other than the fan rooms themselves), and most vulnerable to infiltration of outside air.

Based upon our observations, we could not say with certainty whether or not the building envelope provided an adequate air barrier. We recommended that a blower door test be conducted to measure building air tightness.
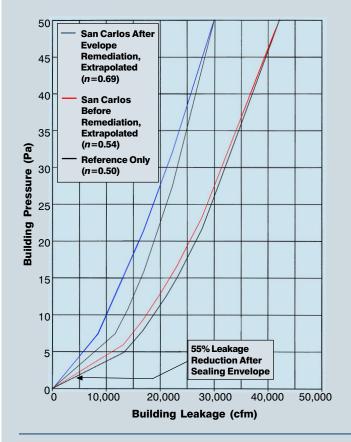
The test was conducted on a Sunday when the building was not in use. Five standard blower doors (calibrated fans) were employed, installed in various exterior door openings. Outside Air Intakes were masked-off. The school had approximately 48 small toilet exhaust fans, which we chose to also mask for the test (they also could have been left open). Representative ceiling return plenum pressures were 0.004 in. w.c. (1 Pa) lower than the occupied space below.

A procedure as outlined above was conducted, resulting in a "rating" of 3.2 ACH50 and 41,991 CFM50. At an inside-out-

San Carlos Park Elementary School

Calculating Outside Air, Leakage

Compute outside air requirement for San Carlos Park Elementary School (after envelope remediation) to replace exhaust air, and maintain a 2.5 Pa (0.01 in. w.c.) positive pressure while overcoming leakage.

Estimated Building Exhaust Requirement
(rounded for this example):

Kitchen Hood Exhaust	_ 8,000 cfm
Less Untempered Makeup Air	6,400 cfm
Net Exhaust From Kitchen Hood	**1,600 cfm**
Toilet Exhaust	+4,600 cfm
General Exhaust (Storage, Janitor Closets, etc.)	+3,800 cfm
Total Estimated Exhaust Air	**10,000 cfm**
Estimated leakage at 0.01 in. w.c. (2.5 Pa)	+ 10,000 cfm 3,281 cfm **13,281 cfm**

Total OA Required, Exhaust + Leakage = 13,281 cfm

Compare Standard 62 ventilation requirements assuming all occupants are students:

1,080 occupants × 15 cfm/person = 16,200 cfm

Standard 62 required ventilation, 16,200 cfm, is greater than that required to pressurize the building and controls the size of the outside air pretreatment system. However, with the building unoccupied and exhaust = 0, the building can be pressurized to 0.01 in. w.c. (2.5 Pa) with only 3,281 cfm.

Figure graph

Legend:
- San Carlos After Evelope Remediation, Extrapolated ($n=0.69$)
- San Carlos Before Remediation, Extrapolated ($n=0.54$)
- Reference Only ($n=0.50$)

55% Leakage Reduction After Sealing Envelope

Y-axis: Building Pressure (Pa)
X-axis: Building Leakage (cfm)

School Statistics

Floor Area	Average Height	Volume
84,000 ft²	9.36 ft	781,200 ft³
1.0 ACH	**Normal Population**	**OA Ventilation @ 15 cfm Per Person**
13,020	1,080	16,200

Comparison Results

Leakage	ACH50	CFM50	Normal (2.5 Pa) — cfm	n (Leakage Curve Exponent)	Improvement @ 2.5 Pa
Before Remediation	3.2	41,991	7,289	0.54	55%
After Remediation	2.3	29,851	3,281	0.69	

Figure 1: Comparison of air leakage at San Carlos Park before and after remediation.

side pressure differential of 0.2 in. w.c. (50 Pa), the building would leak 41,991 cfm (19 815 L/s), the equivalent of the air in the school being changed 3.2 times every hour.

The Florida building code, by comparison, would allow almost double the ACH50 infiltration rate through the air barrier (0.50 cfm/ft² [2.5 L/s per m²] air barrier at 0.1 in. w.c. [25 Pa]).

The test predicted that the school might leak 7,289 cfm (3440 L/s) at 0.01 in. w.c. (2.5 Pa), a reasonable estimate of natural, uncontrolled conditions, i.e., what infiltration might be with the HVAC off.

The 16,200 scfm (7645 L/s) of OA (1,080 students at 15 scfm [7 L/s] each) that would be required during occupied hours was approximately equal to the existing leakage rate plus the kitchen and toilet exhaust. We concluded this was a reasonably tight building, but that it could be improved.

Tightening the building could not reduce the size of a future ventilation air pretreatment system. The most severe weather for this building occurs when it is unoccupied, but it

still requires some cooling to control mold growth. If the building envelope could be tightened, the energy required to offset infiltrating air could be reduced. Some savings in operating costs also would be realized if demand control ventilation (DCV) were used during occupied hours and the amount of OA reduced to only that needed by the occupants. The building would still have to be maintained positive during DCV operation, and sealing the building would maintain the positive pressure with less scfm.

Based upon all of this, the district accepted our recommendation to tighten the building envelope by sealing off the soffit overhang area from the rest of the building.

The soffits were closed up with a polyicynene insulation that is water-blown and reasonably friendly to the environment, and has none of the undesirable smoke and fire characteristics normally associated with foam. It is used extensively in this locality as air and thermal barriers. It lent itself to retrofitting an air barrier to this particular construct by foaming across the gap between wall and roof deck. All intricate, fitted construction work was avoided.

Subsequent to installation, the spray insulation was coated with a latex intumescent paint having flame spread and smoke development characteristics suitable for return plenums.

Building leakage then was retested after the building envelope retrofit, resulting in an ACH50 rate of 2.3 and 29,851 CFM50, a 28% reduction in air leakage at 0.2 in. w.c. (50 Pa). But the building would not be operating at anywhere near this pressure. At the normal, expected building pressurization of 0.01 in. w.c. (2.5 Pa), the new infiltration rate was predicted to be 3,281 cfm (1548 L/s), 55% less than before. This was a dramatic improvement considering that we had started with a relatively tight building (if measured against Florida's hot, humid air barrier standards; this would not be considered a "tight" building in cold climates).

While the energy savings from the remediation will be important to the owner for the remaining useful life of the building, the blower door procedure provided hard, accurate information that HVAC engineers can now use to design a ventilation air pretreatment system correctly sized for the actual building envelope, not some abstract assumption.

Compare and Contrast With System Curve

An HVAC engineer could be expected to assume that air leaking through a given building will behave like a constant mechanical duct system. Once airflow vs. pressure drop under one set of conditions is known, performance at any other condition can be predicted by the relationship:[1]

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$$(\Delta p_2 / \Delta p_1) = (Q_2 / Q_1)^{1/n}$$

For duct systems operating under normal HVAC conditions, $n = 0.5$, and HVAC engineering and air balancing is normally based upon the rule that:

Pressure drop due to friction is proportional to the square of the ratio of the airflows.

Building leakage behaves according to a relationship that can be expressed in this form, but empirical data has shown that the exponent n is in the range of 0.55 to 0.70 rather than 0.50, as most of us always assume. The system curve for building leakage is flatter than a parabola. For a sharp orifice, n may equal 0.60; n could be as great as 1.0, but cannot be less than 0.50 at full turbulent flow.[2]

To illustrate this, we have plotted the leakage curves for San Carlos Park Elementary both before ($n = 0.544$), and after the envelope remediation ($n = 0.69$); and then compared them with a traditional parabola-shaped $n = 0.50$ system curve.

n in these cases is always determined empirically by fitting a curve to the observed data. Estimating the value of n is important because it determines how the leakage curve is interpolated back to 0.01 in. w.c. (2.5 Pa) or some other expected building pressure.

In the case of San Carlos Park Elementary, leakage was estimated to be 7,289 cfm (3440 L/s) at 0.01 in. w.c. (2.5 Pa) before the remediation and 3,281 cfm (1548 L/s) after the remediation. These values were computed using the above relationship, but at the observed n. Had $n = 0.5$, our "normal" value, been used, building leakage would have been estimated to be 8,398 and 5,970 cfm (3963 and 2817 L/s), respectively. It takes less air to pressurize a building than one would expect based upon our normal application of the affinity laws at $n = 0.5$.

We can speculate as to why the building leakage system curve takes on a different shape than we might expect—laminar flow, unpredictable static regain through cracks and passages, etc. But it should be emphasized that the value of the exponent n and the shape of the building leakage system curves is an empirical observation, nothing more.

Impact of Blower Door Test on San Carlos Park

When the HVAC system at San Carlos Park Elementary is eventually upgraded, the quantity of air leakage predicted by the blower door test plus required exhaust air can become the basis for sizing the outside air ventilation pretreatment system. It will turn out that Standard 62-mandated ventilation air exceeds that required for pressurization during occupied periods (*Figure 1*).

Conclusions

Perhaps the most important conclusion is for the HVAC engineer to recognize the concept of building air leakage and

account for it, even if this requires some guesswork. What we don't want to see is designs with OA and exhaust exactly equal, with the leakage term totally ignored:

OA ≠ Exhaust

The identifying mark of a system designed according to this formula is the summation of OA introduced by all of the AHUs will exactly match the summation of exhaust air quantities. Engineers who design along these lines are unclear on the concept of building air leakage and unintentional, uncontrolled airflow.

Knowing how much "to figure" for building air leakage will continue to hamper HVAC design. The testing at San Carlos Park was expensive. Blower door testing will not be cost-effective in all cases. The old models for estimating leakage (such as guessing at an ACH rate) were not all that bad. But as our analytical models improve with the use of computers and the information explosion enabled by the Internet plus ASHRAE's expansion around the globe, we need to recognize that the old models (crackage) were just that — models. They were never intended as gospel. We need to replace them with new models.

If blower door testing were conducted on a large enough sample of buildings, then a database of expected building leakage behavior could be created. HVAC engineers could extrapolate this data as a method for estimating leakage in similar buildings.

In the author's opinion, since both climates and construction practices tend to be "local," these databases should be constructed locally. That work has begun in Florida. The lengthy list of references following Chapter 26 in *ASHRAE Handbook—Fundamentals* indicates that much building leakage data has already been collected.[3] What remains is for the HVAC engineer to discover this data; accept and embrace the idea that some air will leak through the building envelope; make the connection between air leakage and ventilation; and then apply that wisdom to HVAC design.

References

1. *2000 ASHRAE Handbook—HVAC Systems and Equipment*. Formula 1, Page 18.6, Chapter 18.

2. Cummings, J., et al. 1996. "Uncontrolled airflow in nonresidential buildings." Florida Solar Energy Center.

3. *2001 ASHRAE Handbook—Fundamentals*. References at end of Chapter 26.●

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About this Report

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