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Research Overview

Is there an optimum range of airtightness for a building?

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Abstract

Air transport control has been recognized as critical to the proper functioning of buildings. Airflow is related to all facets of environmental control because it influences transport of heat and moisture and affects indoor environment as well as the durability of the building enclosure. To a lesser degree, we also recognize that contamination of wall cavities in building assemblies by organic materials from inside or outside provides both the nutrients and the inoculation potential for mold growth. Moisture carried by air may also increase the rate of emission of volatile organic compounds from these materials. While keeping rain out of building enclosures is a primary consideration in design, controlling airflow through the building enclosure comes a close second in importance to allow environmental control within buildings. Yet, an increase in the airtightness comes with a cost as well as an increased risk of moisture entrapment in case of any failure, and this, in turn, relates to the type of the building.

Keywords

air leakage, air barriers, air flows, airtightness, environmental control, building enclosure

Background

Mechanical engineers recognized that air infiltration takes place through cracks around windows and doors, and this was accounted for in heat loss/gain

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calculations (Hutcheon and Handegord, 1980). Wilson and Nowak (1959) analyzed condensation between panes of double windows and showed that when the neutral pressure plane was at the bottom of the window, the calculated vapor transfer by air leakage was 10 times larger than that gained by diffusion. There was widespread publication of these and similar results (Garden, 1965; Sasaki and Wilson, 1962, 1965; Torpe and Graee, 1961; Wilson, 1960b; Wilson and Garden, 1965), which highlighted the significance of airflow in carrying moisture. Despite a significant number of publications that stressed the need for control of air leakage (Garden, 1965; Tamura and Wilson, 1963, 1966, 1967; Wilson, 1960a, 1961), most building practitioners were still preoccupied with control of the vapor diffusion alone and largely ignored issues of airtightness.

A change in emphasis only came when the field problems confirmed that moisture carried by air was a significant source for interstitial condensation. This was associated with buildings utilizing electric baseboard heating in the 1960s. Builders were attracted to this form of heating because it reduced initial construction costs and eliminated the need for a combustion flue. The higher energy costs were partly reduced by requiring increased levels of thermal insulation. However, elimination of combustion flues reduced air exchange, and higher humidity conditions prevailed in these houses. Condensation problems in attics became more frequent (Orr, 1974; Stricker, 1975) and in flat wooden frame roofs (Tamura et al., 1974). Several studies (Tamura, 1975; Tamura and Wilson, 1963; Wilson, 1960) showed that two interrelated factors influenced indoor relative humidity (RH): changes in efficiency of natural ventilation and changes in the position of the neutral pressure plane.

Moisture is a special class of contaminant because it commonly exists in both liquid and vapor forms and is a limiting factor in the growth of molds and fungus. Poor airtightness that allows damp air to come in contact with cool surfaces is quite likely to lead to the growth of microbiological contaminants. In cold climates, poor airtightness can lead to the formation of ice in and on exterior envelope components. (Sherman and Chan, 2004)

Variations in humidity (Kent et al., 1966) and moisture accumulation in attics and roofs were simply the consequences of these factors (Dickens and Hutcheon, 1965). Measurements of air pressure in houses showed that substantial air leakage occurred in attics and joist spaces of conventional construction. To a great extent, this was caused by the large number of penetrations in the vapor barrier for service ducts and openings. In case of natural or mechanical balanced ventilation, internal overpressure resulted in intensive air and water vapor flow into cold attic. This effect was often called "moisture convection" (Elmroth and Levin, 1983). This problem could be eliminated by exhaust fan that would create in the living space a small underpressure or by means of unbalanced ventilation, but the most reasonable way is to increase air or vapor barrier tightness. This led to recommendations that airtightness of the ceiling construction and partition-to-ceiling details needed to be significantly increased.

The consequences of air tightening and use of increased insulation led to less frequent operation of combustion furnaces. This, in turn, resulted in a reduced rate of air exchange and poorer indoor air quality. Oversized or undersized heating systems and high-efficiency furnaces did not provide the pressure drive needed for adequate air exchange in these tightened buildings, particularly during swing seasons.

In this situation, the model building code of Canada in 1985 required that all dwellings have a mechanical ventilation system and 0.5 air changes per hour (ach), and in 1995, the required ventilation intensity was reduced from 0.5 to 0.3 ach. A report (CMHC, 1990) stated that above 0.3 ach, concentrations did not change much. More recent studies (Offerman et al., 2008; Willem et al., 2013) generally agree with this limit although reduction in formaldehyde continues as the rate change increases. For humidity in the air, the situation is even more complicated.

Introduction of mechanical ventilation set the stage for further improvements to airtightness of the houses. During this period, the concept of air barrier (AB)/vapor barrier was introduced. Soon, however, Karagiozis and Kumaran (1993) showed that most of continental North America does not require vapor barrier with the permeance lower than 3–6 perms or 200–400 ng/(m^2 s Pa). A consensus has developed that critical to the success of buildings is the systems approach (CHBA, 1989) that integrate energy efficiency and healthy indoor environment. New design tools enhanced tradeoffs between the design of the enclosure and equipment to meet energy targets.

The following were the critical technical requirements for Canadian R-2000 program and following it the Building America program in the United States:

- Use of mechanical ventilation;
- Requirements for an AB system;
- Design to avoid thermal bridges;
- Control of moisture entry from the ground;
- Voluntary testing of the ventilation system.

In the 1995 edition of the NBC, the AB system was required to satisfy the following requirements:

- There should be a material layer intended to provide the principal resistance to air leakage with an air permeance not greater than 0.02 L/(m^2 s) measured at 75 Pa difference. This is a material air permeability requirement measured with a test such as that proposed by Bomberg and Kumaran (1986).
- All components of the AB system shall comply with durability requirements specified by respective material standards.
- The system shall be continuous across joints, junctions, and penetrations.
- The system shall be capable of transferring design wind loads.
- The system shall be evaluated with deflections reached at 1.5 times the specified wind load.

Two alternate approaches to air leakage control were earlier introduced—the airtight drywall approach (ADA) and the external airtight sheathing element (EASE). The ADA system was developed by Lstiburek and Lischkoff (1984). Using gaskets and controlling terminations of the drywall sheets, they achieved relatively airtight buildings. The vapor resistance was provided by the use of paint on the drywall. The measures to achieve airtightness involved the use of both polyurethane foam and neoprene gaskets at the termination of the drywall.

While ADA systems have been shown to work well in single-family houses, designing to minimize flanking sound transmission in row housing and apartment blocks led to considering alternate approaches. Application of EASE by providing a continuous layer of thermal insulation on the exterior reduced effect of thermal bridging and reduced the risk of condensation in the wall cavity by increased temperature on the surface facing the wall cavity in wooden frame wall. Recently, the requirement of minimum R5 continuous exterior insulation has been added to the Canadian Building Code.

Terminology related to ABs

We need to define different concepts of airtightness since each of them has particular applications but is only partly related to others:

(1) Material airtightness is measured in laboratory on material alone; *we will not use it in practice*.
(2) Joint airtightness is either laboratory or field measurement that can be expressed as airflow per unit area of wall or per lineal measure of wall or window.
(3) Plain wall airtightness, measured in laboratory, typically on 8 ft × 8 ft plain wall, can be used as a benchmark (Quirouette, 1985; for testing details, see NRC, 1988, 1990; MH, 1991).
(4) Envelope airtightness (EA) is the typical test of the whole-building enclosure.
(5) Envelope section airtightness (ESA) can be determined in two different ways:
    - Measured directly on a section of the envelope, for example, using a box attached to the wall with window;
    - Evaluated from multizonal network models and airflow perturbations (Lstiburek, 1998; Lstiburek et al., 2000, 2002) or by similar method to separate the section from the surrounding space.

While the above laboratory tests are important for manufacturers, they will not necessarily predict field performance of the envelope. The situation in the field involves more complicated pathways, including those between different zones and through interior partitions. Furthermore, the field test involves a dynamic response

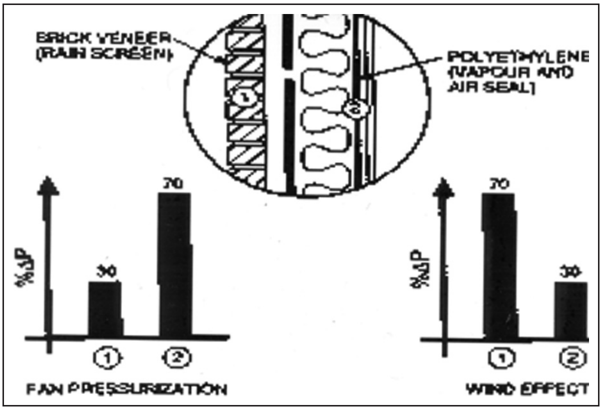

Figure 1. Polyethylene film (air/vapor barrier) is the designated air barrier material, but fan pressurization and wind effects show different significance of brick veneer and polyethylene.
Source: Quirouette (1985).

of building that in many instances is quite different from the static. Figure 1 highlights such a situation.

Need for testing airtightness

Airtightness is important from a variety of perspectives, but most of them relate to the fact that airtightness is the fundamental building property that affects infiltration. Infiltration is the movement of air through leaks, cracks, or other adventitious openings in the building envelope.

Airflow is one of the most important mechanisms for moisture flow in wooden frame walls. However, characterization and quantification of the effects of airflow have been elusive. The amount of air infiltrated into a building is determined by the airtightness of the building envelope and the pressure difference between inside and outside the building.

In houses with natural ventilation, temperature difference and wind-induced pressure difference are the main factors of air exchange intensity. This means that if the minimum requirements for air quality are to be maintained during the whole year, prevailing ventilation intensity is excessive. This fact may not be accepted any longer when we have to design and build zero energy building (ZEB) or net zero energy building (NZEB). In buildings with designed ventilation systems, especially those with heat recovery, airtightness may be a determining factor in the performance of that system (Sherman and Chan, 2004)

Poor airtightness allows air to be drawn from contaminated areas; indoor air quality can be reduced although total ventilation may be increased. Improved tightness may allow to achieve higher underpressure and ensure good indoor air quality in bedrooms at the leeward side (Gids and Borsboom, 2012).

In low-energy buildings equipped with mechanical ventilation heat recovery, high airtightness may be beneficial in terms of energy use, and however, it may have a positive effect on indoor air quality but only when it works correctly (Carrie and Wouters, 2012). In building practice, it is not an evident perspective.

However, it is not quite evident that a building should be as tight as possible. It is also very important to implement the obligatory requirements of minimal values of airtightness. Apart from minimum fresh air delivery and moisture removal, these requirements ensure right direction of airflow and allow to overcome back drafting (Gids and Borsboom, 2012). Because the real pattern of airflow in building is in fact not known, more intensive air exchange than theoretical minimum would guarantee some safety margin for indoor air quality assurance. Experience with renovation of existing buildings also proved that users did not change their habits after tightness improvement. What was acceptable during use of the leaky building resulted in moisture buildup, mold growth, and moisture damages after building refurbishment (Erhorn-Kluttig and Erhorn, 2012).

A combined approach may also be observed; however, requirements regarding airtightness and minimum air leakage area are specified to secure rational energy use and indoor air quality (Carrie and Wouters, 2012). The airtightness can vary throughout the building due to different wall sections with or without windows, corner sections, with or without doors, and so on. The pressure difference also varies throughout the building envelope because the pressure distribution around a building is nonuniform and dependent on wind speed and direction, and the indoor–outdoor temperature difference varies depending on the building shape and dimensions. Therefore, it is necessary to understand the connectivity of the exterior envelope with internal partitions, walls, and floors. The field testing methodology has largely been focused on air leakage of the whole building. Relation between laboratory airtightness of a wall assembly (clear wall) and that of the assembly in the building is, at best, tenuous. Not enough focus was given to the connectivity within buildings.

Effectively, one needs airtightness of building enclosures for the following reasons:

- To better control air exchange intensity and adjust it to the needs;
- To reduce the amount of moisture carried by the moist air (indoor in cold climates and outdoor in warm and humid climates) and thereby increase *durability* of the construction;
- To reduce the amount of volatile organic compound (VOC), particulate, or mold spores carried from the outdoor or from construction materials used in the wall assembly into the indoor space and thereby *maintain healthy indoor environment*;
- To reduce the amount of uncontrolled airflow (UAF) in the wall assembly (driven by wind and temperature differences) and its effect on *hygrothermal performance* of the assembly;

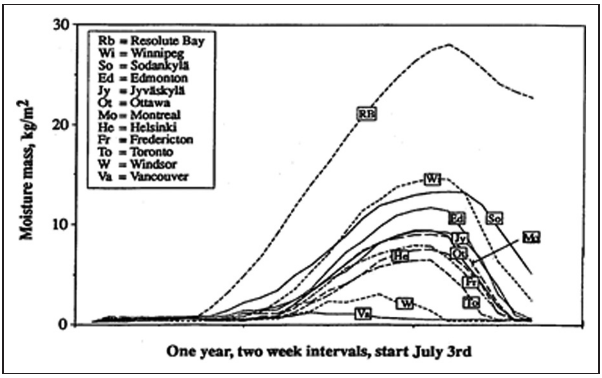

Figure 2. Amount of moisture deposited (kg/m^2) at different climates, when indoor air with a temperature of 21°C and 35% RH passes through the wall at the rate of 0.9 L/(m^2 s Pa) at 50 Pa as a function of time in the year.
Source: Ojnanen et al., 1994, Ch 2. Moisture Control in Buildings, Trechsel Ed., 1st edition, Fig 18, p. 30

- To reduce the amount of *heat/cold gain or loss* caused by the air entry having temperatures different from that in the conditioned space;
- To control and balance air exchange between separate zones or rooms.

The required level of enclosure airtightness should depend on the outdoor climate as well as the indoor conditions. Figure 2 shows the amount of moisture (kg/m^2) condensed from airflow with a temperature of 21°C and 35% RH entering the wall at a rate of 0.9 L/(m^2 s Pa) at 50 Pa at different locations as a function of season. In some cases, energy efficiency may overweigh the durability considerations, and in other cases, the opposite will be the case. For instance, looking from moisture accumulation over the year point of view, locations such as Toronto or Helsinki appear to have much higher risk of durability than Vancouver.

The model shown in Figure 2, for the sake of global comparison, used a low level of RH in winter. This is incorrect for the climate of Vancouver. (We are not sure whether this model differentiated between the incidence of driving rains in the coastal area vs continental climate of North America.) Figure 3 shows a rainfall map, and as we know that in Vancouver the rainy season coincides with mild winter, we can easily understand that the decay potential for wood in Vancouver is much higher than that in Toronto.

We brought this example to illustrate that one cannot use only one part (however critical) of the complex phenomena to predict the outcome. For moisture-originated durability, it is not only the wetting potential but also its relation to the drying ability that decides upon moisture balance. Furthermore, moisture is only one part of the environmental complex (heat, air, and moisture flows). We need to address this complex simultaneously because of the strong interactions between

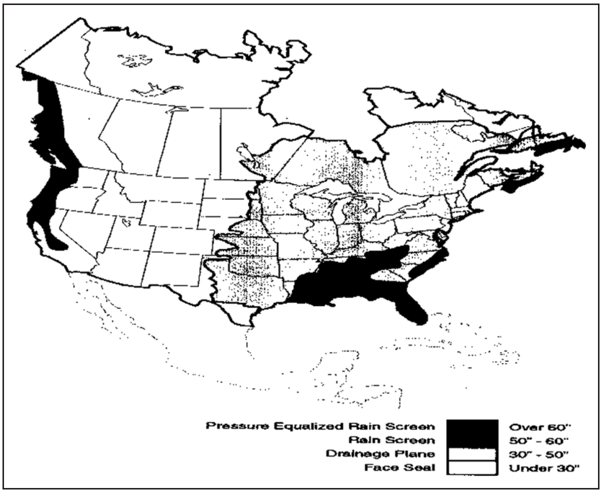

Figure 3. Map of rainfall in North America indicates regions with higher incidence of durability problems.

those three phenomena. Incidentally, because of mild climate on the Pacific coast in this region, the air leakage through building enclosures is much higher in comparison with the central part of North America, and this increases the incidence of durability problems.

As long as buildings were leaky and poorly insulated, the effect of heating, ventilating, and air conditioning (HVAC) systems on air pressure was insignificant. There was no need to understand air movements in the building, other than providing a necessary supply of fresh air. This is not the situation today. Now, we have well-insulated airtight buildings and in which there is a potential for increased health problems caused by mold or microbial contamination, if the system does not work properly. Today, air pressure fields may have an important effect on the performance of building enclosures, and understanding of air movements in buildings is a necessity. The determination of air pressure differences, however small and difficult to measure, is needed to establish performance of the building as a system.

A strategy to control air pressure in the building space includes the following steps:

(1) Enclose the air space and quantify the degree of airtightness;
(2) Use controlled mechanical ventilation;
(3) Control air pressure fluctuations induced by HVAC system operational conditions;
(4) Control air pressure gradients induced by HVAC system operational conditions;

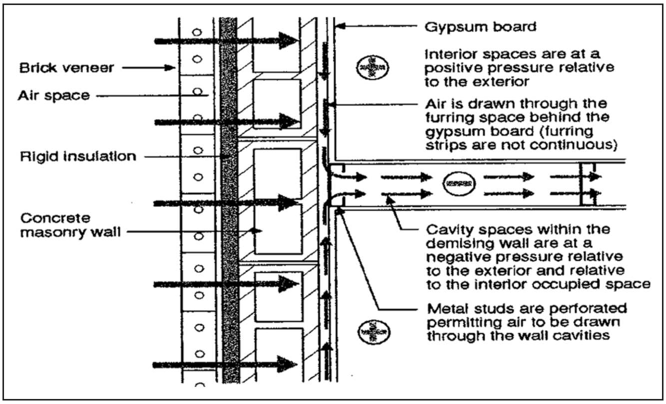

Figure 4. Cavity in the demising wall is connected with the furring space in the exterior wall extending the effect of the leaky duct for a great distance. Moist outside air was drawn into the building cavities despite the positive pressure in the interior occupied space and mold grew on the interior wall.
Source: Lstiburek (1998), with permission.

(5) Eliminate interconnected internal cavities communicating with HVAC systems;
(6) Review the building mezzo-climate for differences in wind and solar shading conditions.

The effect of pathways created by external cavities and interconnected internal cavities communicating with HVAC systems on performance of building systems is often neglected (Figure 4). The significance of these elements has been illustrated in the few examples selected from case studies (Lstiburek, 1995, 1998, 2002, Lstiburek et al., 2000). Some other cases listed by Lstiburek (1998) are as follows:

- A facility located in a cold climate with inadequate provision for return air. When interior doors were closed, individual rooms/spaces became pressurized with respect to common areas. The common areas, in turn, become depressurized. When atmospherically vented combustion appliances (such as fireplaces and gas water heaters) were located in the common areas, the negative pressure in these regions led to back drafting of combustion appliances. In the pressurized rooms/spaces, the forced exfiltration of interior (typically moisture laden) air led to condensation and moisture-induced deterioration problems (Figure 5).
- Hallways and corridors can cause an extension of pressure fields throughout a building. A typical hotel room ventilation system may have a bathroom exhaust operating on a continuous basis via a rooftop-mounted exhaust fan (which also serves for other bathrooms). Make-up air for this bathroom exhaust is typically provided through the exterior wall via a unit ventilator

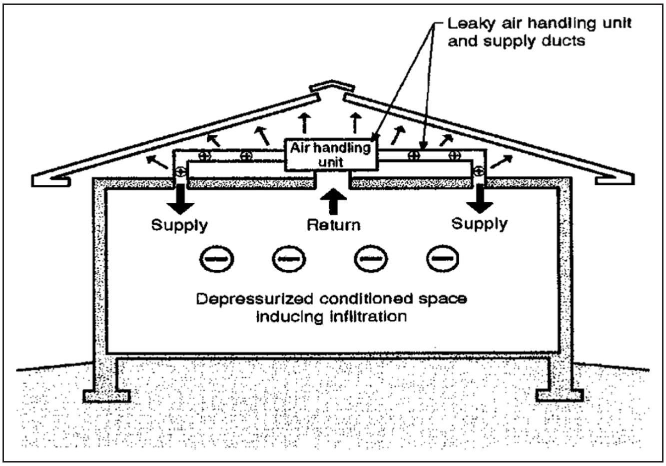

Figure 5. A facility located in a hot, humid climate with leaky supply ducts located outside the conditioned space in a vented attic. Air leaking out of the supply ducts depressurized the conditioned space, inducing the infiltration of exterior hot, humid air.
Source: reprinted with permission from Lstiburek (1998).

or packaged terminal heat pump (PTHP). In the case investigated, the design assumed that 60 cfm out through the bathroom was offset by 60 cfm through the unit ventilator or PTHP. Although the unit ventilator or PTHP did not run continuously, an intermittent imbalance of 60 cfm was not considered to be a problem. Now, consider 30 hotel rooms on a floor served by a single corridor. This corridor becomes a large duct connecting all rooms on the floor. With 30 exhaust flows of 60 cfm each, if they operate continuously, an 1800-cfm exhaust is created on the floor. Unit ventilators or PTHPs are only operating on a 20% duty cycle (i.e. 80% of the units per floor are not operating at a given time). The supply air was only 360 cfm (six operating unit ventilators of PTHPs at 60 cfm each). The flow imbalance was 1440 cfm, and this was sufficient to depressurize the entire floor. In hotel located in hot and humid climates, the negative pressure field created in this manner is the single, most significant reason for mold, odor, and moisture damage (Figure 6).

These observations highlight that air leakage/pressure relationships are the key to understanding the interaction between the building enclosure and the HVAC system. To design and build safe, healthy, durable, comfortable, and economical buildings, we must control pressure fields.

Air leakage of a building

Typical relation between the air leakage and pressure difference between the building and its environment is expressed by equation (1)

$$Q_a = C\Delta p^{\beta} \tag{1}$$

where C and β are experimental coefficients. The pressure exponent is normally found to be in the vicinity of 0.65 but has the limiting values of 0.5 for a turbulent flow and 1.0 for a laminar flow.

The power law has been found to be a reasonably good empirical description of the flow versus pressure relationship; it does not correspond to any physical paradigm. There are physical paradigms that could be applied to the problem of airtightness:

- If the leak is very short, frictional forces in the leak itself can be ignored and the leak may be treated as an orifice in which the flow is proportional to the square root of the pressure drop. The higher the flow rate (i.e. Reynolds number), the longer the leak can be and still be treated as an orifice.
- If the flow rate (Reynolds number) is low enough, the flow will be dominated by laminar frictional losses and the flow will be linearly proportional to the pressure drop.

Comparing the power law, the first case corresponds to an exponent of 0.5, while the second case corresponds to an exponent of 1. The fact that measured data typically result in an intermediate value indicates that neither of these two limits is a good explanation (Walker et al., 1997).

Until now, we discussed two independent and not correlated measures. One related to the quality of construction and dealing with airtightness of the building enclosures is expressed in L/(m^2s) at 50 Pa or in m^3/(m^2 h) also measured at 50 Pa, and another measure that is related to ventilation is expressed in air changes per hour. The first measure relates to the area of enclosure, while the second is more related to the floor area and number of occupants because of the ventilation role in diluting the level of pollution. Now, the question is whether one can correlate these two measures.

Requirements for airtightness vary, but typically building should not have air leakage higher than 3 m^3/(m^2 h) when tested with 50 Pa pressure difference. For a bungalow with 110 m^2 floor area, 440 m^3 heated volume, and 220 m^2 envelope surface area (i.e. the ratio of the envelope area to volume (A:V) = 0.5), this would imply 660 m^3/h, that is, 1.5 ach. Assume a value of β = 0.65 and recalculate this requirement for Δp of 4 Pa pressure difference. One obtains 0.3 ach at the standard conditions. Air change rate is commonly used as a simple building tightness measure, but because of its dependence on shape factor (external shall area to volume ratio) air leakage rate, expressed as a ratio of air volume to floor area and unit time, this is more objective and commonly used information. Liddament (2012) showed relation between envelope area, air change rate, and air leakage rate (permeability). Almost the same air leakage rate may be related to large buildings with low air change rate and small buildings with double air change rate.

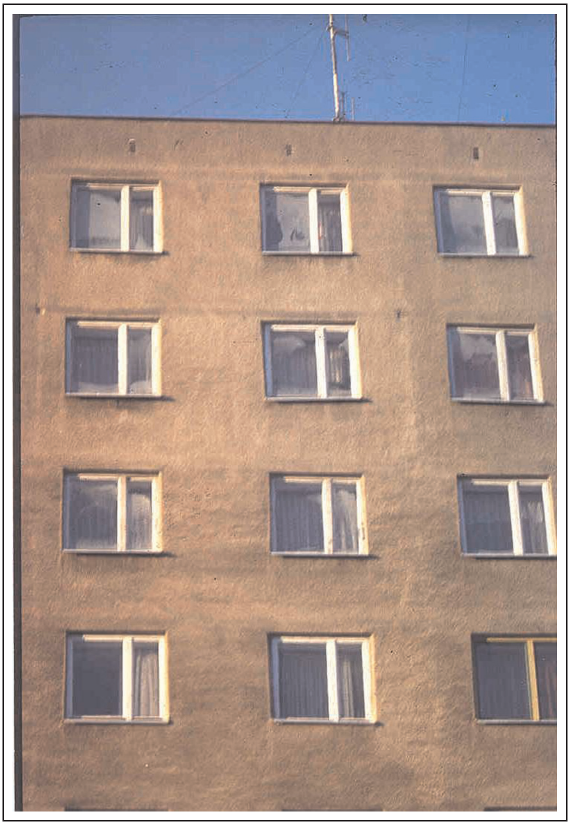

Figure 6. Tall building in cold climate in Europe, in winter. Stack effect caused air exfiltration demonstrated by frost visible on external glazing surface in double windows on the top floors, while those at the bottom of the building are clear. The connecting element for airflows here is a staircase.

For residential occupancy, one may require the use of mechanical ventilation conforming to the rates required by ASHRAE Standard 62.2-2013, "Ventilation for Acceptable Indoor Air Quality." Airtightness requirements for the building enclosure are more confused because of three levels of air leakage control:

(1) Level of material, so-called plane of airtightness in the cross-section or the principal resistance to air leakage through materials;
(2) Level of wall assembly, with joints between material sheets, for example, sheathing boards. This level would typically include connection between wall and window;

(3) Level of a building with staircases and ducts and frequent use of a return plenum joining different indoor spaces in office buildings.

Despite the lack of documented correlation between these three levels of airtightness, the North America codes elected to draw attention of designers through stringent material requirements, hoping that

- Restricting air leakage through the material to no more than 0.02 L/(m^2 s) measured at an air pressure difference of 75 Pa would ensure
- Air leakage through the wall assembly to no more than 0.2 L/(m^2 s) measured at an air pressure difference of 75 Pa, and this in turn perhaps would ensure
- Enclosure leakage no more than 2 L/(m^2 s) at 75 Pa pressure difference or 1.5 L/(m^2 s) at 50 Pa pressure difference through the building envelope of the house.

How this requirement compares to airtightness in real buildings? It agrees with the average of low-energy houses tested in 1980 in Saskatchewan (BRN 178) expressed as

$$Q_a = 0.0169\Delta p^{0.703} \tag{2}$$

With $\Delta p = 50$ Pa, one obtains 1.45 ach.

Survey showed that at 50 Pa, the average airtightness of the R-2000 houses (model houses introduced in 1980s) varies from 1.15 to 1.35 ach. Obviously, the "standard" houses in the United States and Canada have much lower airtightness.

Several measurements were performed on large apartment buildings with balanced fan depressurization technique. The results varied from 3.2 to 5.2 L/(m^2 s) at 50 Pa for one building and 2.3 to 3.6 L/(m^2 s) for three other buildings (5–17 stories high). These leakage characteristics are 3–6 times higher than the requirements for a tight house.

Full-scale testing was performed in Norway and focused on differences between laboratory and field performance of materials used to secure airtightness of the wall. There was no difference between air permeability of continuous materials. The differences were, however, very significant on the joints. Building papers with nailed list on joints showed 10–30 times larger air permeance than the material itself. The air permeability measured in laboratory for these two types of building papers were 0.0012–0.0015 m^3/(m^2 h mm H_2O), which corresponds to air permeance of 0.0025–0.003 L/(m^2 s) measured at an air pressure difference of 75 Pa. The values measured under field conditions with "nailed joints" at 75 Pa pressure difference were 0.025 and 0.12 L/(m^2 s).

These differences put in question the need to require material to have airflow lower than 0.02 L/(m^2 s)—when joints increase the air leakage through the wall assembly by a factor of 10. Incidentally, an open-cell polyurethane foam that does not qualify as a material for AB system is often successfully applied in AB systems that fulfill all the requirements of the system.

Furthermore, the typical leakage through the building envelope also depends on the pressure distribution in the building space, that is, depends on many other factors related to the building HVAC and occupancy. Yet, before addressing this question, one needs to review methods for testing air leakage through the buildings.

Methods for airtightness testing under field conditions

Typical airtightness test, such as *Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method*, is suitable to measure a single zone where the entire space is pressurized or depressurized in a uniform manner. Blower door technology was first used in Sweden around 1977 as a window-mounted fan (reported by Kronvall, 1980) and to test the tightness of building envelopes in. This same technology was being pursued by Caffey (1979) and Harrje et al. (1979) at Princeton University to help find and fix the leaks (Sherman and Chan, 2004).

Fan depressurization (EN-ISO 13829) and pressurization (ISO 9972) methods

Assuming that the quantity of air exhausted by the blower is returned by the air leakage under the measured pressure (Figure 7), one can calculate the two coefficients in the equation $Q = C\ \Delta p^n$.

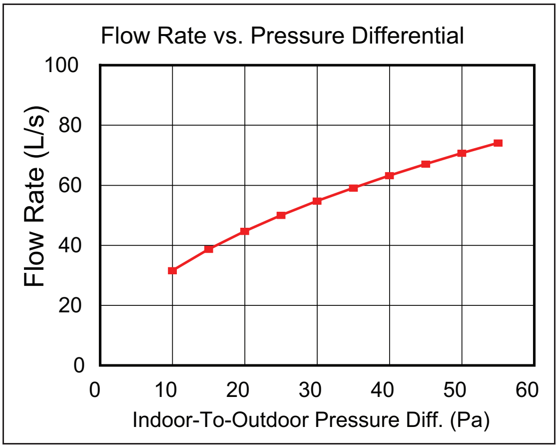

Figure 7. Typical data when measuring single zone by fan pressurization or depressurization method.

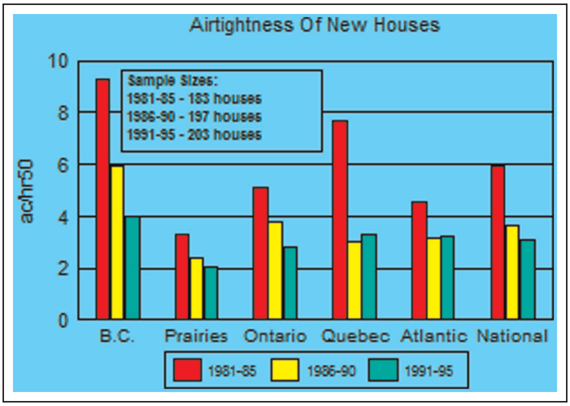

Figure 8. Airtightness of houses in Canada measured from 1981 to 1995.
Source: Proskiw (1998).

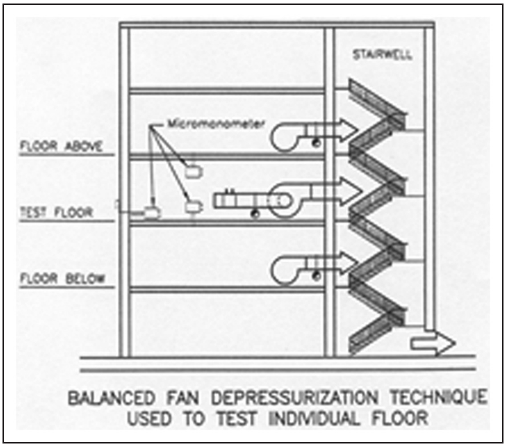

Figure 9. Balanced fan depressurization technique to test individual floor.
Source: Proskiw (1998), with permission.

One can observe the effect of climate as follows: from mixed climate of British Columbia where 1990s average was 4 ach, through Quebec and Ontario with averages near 3 ach to the most severe climate of Prairies where the average airtightness went down to 2 ach (Figure 8).

Now, if we want to study a large building where only one zone is of our interests, we could use three blower door techniques (Figure 9) to set the same pressure conditions and thereby compensate for airflows to the adjacent space. In addition to being expensive and difficult to perform, this method does not allow eliminating the effect of penetrations between these zones.

Parallel flow airtightness test

Parallel flow airtightness test (PFAT) is based on using two blower doors (Proskiw, 1998) and allows measuring one part of the multizonal building. This procedure consists of four steps:

> *Step 1*: Install blower door between zones A and B. Keep zone B open to the outside and measure flow from zones A to B. Observe that the results of this test include airflow from zone B to zone A because there will be a pressure difference between zones A and B.
>
> *Step 2*: Install blower door in zone B and exhaust to the outside. Next, switch off blower door in zone B and start one in zone A and measure pressures differences from zones A to B and from B to the outdoor; these are considered as the initial set of conditions $Q_T = Q_A + Q_B$; Δp_A and $\Delta p_{B.}$
>
> *Step 3*: Adjust blower door in zone A to measure the same pressure difference between zones A and B which will be the same as measured in step 2 as Δp_A.
>
> *Step 4*: With the air leakage across the exterior wall the same as in step 2, we may write a series of equations describing for the partition between A and B the difference in the airflow
>
> $$\Delta Q_T = Cp\left(\Delta P^n_{binitial} - \Delta P^n_{bfinal}\right)$$
>
> and using the two tests on the blower door B, we can solve the equations. An additional criterion used in this method is that coefficient n must be falling in the range of 0.5–1.0 or the test is discarded.

The method was verified in the laboratory and field application and found suitable for practical applications. Some Lawrence Berkeley National Laboratory (LBNL) researchers (Hult et al., 2012, 2013; Hult and Sherman, 2014) recently did more work in this area.

Using perturbations and inverse of multizonal flow solutions

While two blower solutions are very useful for assessment of parts of the building separated with doors, one may need to address a specific part of the building enclosure, for example, a room where people complain about the presence of odors where using the two blower doors is not possible. A technique used by Lstiburek (1998) and based on solving several multizonal flow equations using a blower door and flow model, for example, CONTAM and perturbations by opening and closing windows and doors, may, therefore, be used. It is strongly recommended that this technique is used in conjunction with the PFAT method because of the uncertainty in the inverse solution of the multizonal flow system.

Gas tracing method

Pressurization methods describe airflow at conditions different from real operating conditions in building. However, it has advantage and disadvantage. It is advantageous because it is mostly independent of weather conditions and obtained results enable building tightness rating and disadvantage because it gives no information about actual ventilation capability. The opposite is true for gas tracing method, which allows determination of instantaneous flows in relation to actual interior and exterior conditions (temperature and wind). Measurement method is based on either multiple or continuous tracking of concentration of a gas that was introduced into the tested building space. The simplest measurement approach is concentration decay method, where tracer gas is supplied once to the tested space and air exchange rate is evaluated based on the concentration decay data obtained (EN-ISO 12569) by equation (3)

$$C(t) = C_o \cdot e^{-nt} \tag{3}$$

where C is the concentration as a function of time, C_o is the initial concentration, and n is the air infiltration rate (1/h).

This method assumes ideal mixing of air and tracer gas. To ensure good measurements with tracer gas, we require that it has never been present in real conditions, that is, it has density close to air and if possible is mechanically mixed with air. But, in fact, mixing itself can also influence a process of air infiltration by changing internal temperature distribution and/or stratification. In case of displacement ventilation method, forced mixing would completely upset assumed air stratification.

Another problem is connected with uneven trace gas concentration in the whole space volume, especially in big spaces or complicated building geometry. This problem can be dealt with as follows:

- Air samples are collected at a number of points to establish the path of the flow (Sherman et al., 2014).
- Measurements are conducted at several points near the air escaping the building, and the average value is used when calculating ventilation rate (Elmroth and Levin, 1983).

In addition to the one presented above, two other tracer gas methods can be used (EN-ISO 12569):

- Continuous dose method;
- Constant concentration method or their combinations.

Selection of the method depends on a building structure, kind of ventilation system, building use, tracer gas and detection system availability and cost, and so on. In the case of multicell spaces, the constant gas concentration method is the only one that may yield reliable results because it is not affected by cross-flows of air between building cells or zones.

A wide choice of tracer gas is available now, each of them characterized by individual set of advantages and restrictions (EN-ISO 12569): helium, carbon dioxide, sulfur hexafluoride, perfluorocarbon, ethylene, and nitrogen monoxide. Of them, CO_2 seems to be the most common, easy to track, and harmless substance, considering global warming potential or flammability and when measurement does not require critical accuracy. The main problem with CO_2 as a tracer gas is that it is usually generated in buildings by the occupants and the other sources. CO_2 generation rate must be known in order to measure its concentration changes due to air leakage.

Discussion on air control issues

Current trends toward sustainable buildings bring about a need for a fundamental revision to many design premises that have been developed over the years. The most important change is the need of integration in the processes of design, construction, quality assurance, and commissioning. The interaction between mechanical systems and building envelopes becomes very significant and affects practically every aspect of the built environment. Issues such as indoor air quality; fire protection (smoke, toxicity, and fire spread); durability (moisture accumulation); comfort (temperature, RH, and odors); and cost of operation and maintenance are strongly related to airflow control. This integration must be better understood to avoid costly mistakes when introducing new technology.

The advent of low-energy buildings (near ZEB or NZEB) brought us interacting design of the building enclosure and HVAC systems because both of these systems affect wetting and drying of walls, rain penetration, pollutant migration, and the durability of the building envelope. In turn, all these phenomena are centered on heat, air, and moisture movements that we label as the environmental control. Of these three transports, controlling air movements is probably the most important, and we shall use the term introduced by Lstiburek (1998)—we need to control the air pressure response of the building.

Air pressure differences are small, typically in the range of 0.5–2 Pa, but they have significant effects on building performance. Lstiburek (1998) stated,

> In most mid-rise and high rise buildings the stack effect air flows typically dominate the HVAC system air flows … Air flows from the lower units and floors, up the elevator shafts, stairwells and service penetrations to the upper units and floors. These stack effect induced air flows are responsible for pollutant migration, odor problems, smoke and fire spread, elevator door closure problems, and high thermal operating costs.

> By sealing units from corridors and by isolating corridors from elevator shafts (vestibules) stack effect air flows are significantly reduced. The pressure drops are now taken across the corridors and elevator vestibules, not the exterior building envelope. This results in a safer building with respect to smoke and fire control. Indoor air quality problems are reduced and energy efficiency is greatly enhanced.

While air transport control is now recognized as a critical issue in design of the building enclosures, achieving a balance between information needed for energy efficiency, indoor environment, and durability is still a challenge. It is easy to say that one need to analyze the hygrothermal performance of the whole building while one examines the building enclosure, but there is no readily available linkage between airtightness of the building enclosure and ventilation of the indoor space.

Lstiburek (1998) stated,

> Leakage area measurements give only one part of information. Even if total leakage area is known, utilizing wind and stack forces for air change is unreliable and uncontrollable due to the variability of weather and shielding factors. Distribution of leakage areas and air pressure relationships from wind and stack forces cannot be determined. Therefore, controlled mechanical ventilation is a requirement in all buildings regardless of building envelope tightness, in order to insure indoor air quality, health, and safety.

Ventilation serves two purposes: (1) source control to remove pollutants, for example, exhaust in kitchen and bathroom, and (2) whole-house ventilation for removal of other pollutants. Typically, the whole-house ventilation works in an intermittent way (defined as a fraction of each hour during occupancy that is needed to provide the required amount of air involving air distribution systems and may also involve a degree of mixing). Air distribution system is to make sure that delivery/exhaust (or both) takes place in each room. If the building is provided with source control, mixing can be introduced either by the interior airflow organization, for example, supply air to the bedrooms and exhaust from the kitchen, or through bypass on the heat recovery ventilation (HRV). The latter may be preferred for periodically used spaces and requires advanced controllers. For equivalency of intermittent ventilation and dynamic controls, see Turner and Walker (2012, 2013) and Sherman and Walker (2011).

Finally, we need to come to the recommendations for the range of airtightness for contemporary buildings. Over the years, many works reviewed the relation of building enclosure airtightness to the air infiltration (ventilation) requirements, starting with Shaw (1981) to Chan et al. (2012a, 2012b); Sherman et al., (2011) and Walker et al. (2013) where the latter works are based on more than 140,000 homes database. It is evident that no single value will be recommended

We also know that for designing low-energy buildings (now are called *zero energy ready* buildings), we cannot use one template for all climates. For example, the current limits in United Kingdom, especially for small dwellings, are much higher than those given in 1980 Swedish Building Code. UK requirements proposed for 2016 will be close to 1980 Swedish regulation (Liddament, 2012).

To design ZEB, we need to consider peak loads and average energy use in heating and cooling; all of them are climate related. Airtightness must also be adequate to satisfy moisture-originated durability considerations. Furthermore, as air leakage relates to the area of exterior walls, it relates to the building shape and size. Last but not least, at the high end of airtightness, there is additional cost of testing. Gids and Borsboom (2012) emphasized the differences between building technologies and their differentiated airtightness feasibility related with this action costs. It does not seem rational to set tightness requirements at the same level in each case. Erhorn-Kluttig and Erhorn (2012) suggested a significance of incentives when reaching very high tightness rather than obligatory requirements.

For small buildings in cold climate, the benchmark of the building enclosure is from $3\,\mathrm{m}^3/(\mathrm{m}^2\,\mathrm{h})$ or $0.8\,\mathrm{L}/(\mathrm{m}^2\,\mathrm{s})$ or 1.5 ach, which is much higher than maximum allowable value for European passive house. This requirement represents a typical tight house built in Canada, while in Europe 1.5 ach is in many countries required for buildings with mechanical ventilation, regardless of their size. However, in the case of large buildings, very good results, especially when expressed as air changes per hour, are easily achieved due to the beneficial ratio of external area and volume. In Europe, requirements for large building start at the level of $3.0\,\mathrm{m}^3/(\mathrm{m}^2\mathrm{h})$ and go down to $1.25\,\mathrm{m}^3/(\mathrm{m}^2\,\mathrm{h})$ and even $0.6\,\mathrm{m}^3/(\mathrm{m}^2\,\mathrm{h})$ in Luxembourg (Simons and Rolfsmeier, 2012).

Finally, most of the benefits of testing airtightness are realized when the tests are performed during the construction process and assist the builder in improving the quality of the construction. Doing them after the construction has been completed means missing the opportunity for improvement.

Since the wall–floor, wall–window, and wall–roof connections at the top floor are the typical locations of faults, we recommend using pressure boxes for small-sized components combined with blower door and infrared testing. Thermal imaging proved to be efficient tool of building quality control, but when combined with relatively large pressure difference during blower door test, it gained extra importance.

What is also important, infrared testing of building tightness may be easily extended beyond cold season conditions. Thermal image shown in Figure 10 was taken during very hot period. Because of efficient thermal insulation of walls and windows (triple glazing), high airtightness, and massive structure, the indoor temperature in tested building was 11K lower than ambient temperature without mechanical cooling.

Infrared picture in Figure 11 was taken during cold season. Underpressure in a building resulted in a characteristic pattern of low temperature distribution on window sill.

Not only artificial pressure difference may be used to detect air leakage but also natural pressure difference induced by wind, especially in the case of high-rise

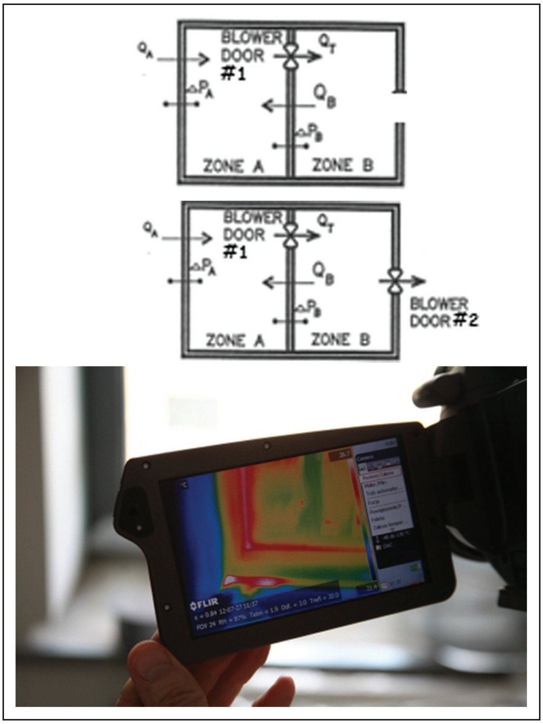

Figure 10. Combined blower door and infrared test of a passive school building: $\Delta p = -100$ Pa, $T_e = 32°C$, and $T_i = 21°C$. Despite a special sealing system around the wall–window connection, warm external air leakage was observed (authors' archive).

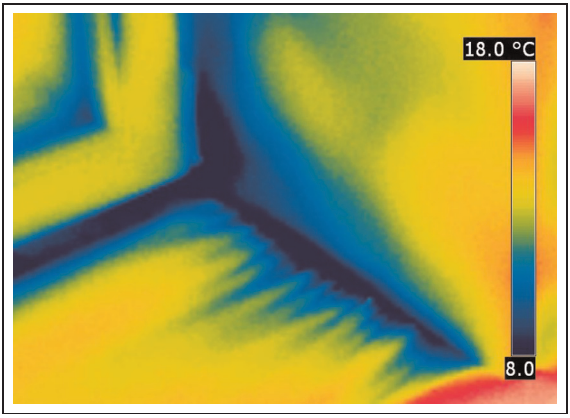

Figure 11. Combined blower door and infrared test: $\Delta p = -50$ Pa, $T_e = 3°C$, and $T_i = 18.3°C$ (archive: Termocent).

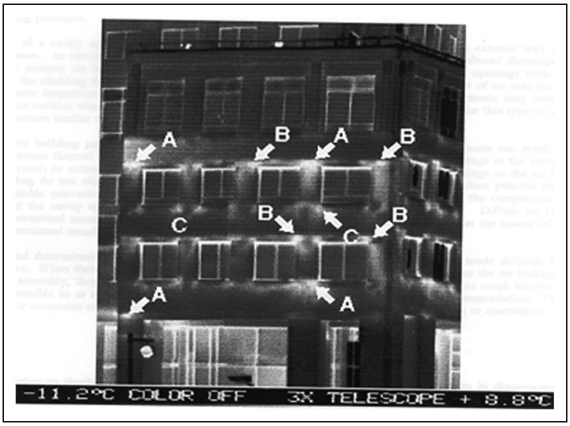

Figure 12. Infrared picture shows places of warm air escape through the wall.
Source: courtesy of Tony Colantonio, Natural Resources Canada (NRCan).

buildings. Exfiltration of warm air through leeward walls due to low external pressure may be easily observed by means of thermal camera.

Need for future research

We have postulated (Bomberg et al., 2015) that the role of Building Physics is changing from following the construction practice to leading innovation because an integration of testing and modeling permits addressing the real-time calculations and design adapted to the climate and service conditions. To this end, we need to upgrade hygrothermal models to include the effect of airflow on thermal performance of the wall and specifically walls with ventilated cavity integrated with heating or cooling. This may also involve a look on interzonal airflows and comparison with their prediction by a model.

While moisture flow under field conditions can already be incorporated, it is not the case with airflow. To this end, we are missing the methods for determination of the average path of airflow in real buildings. Figure 12 shows that air escapes out of building mainly through wall–window interface. But we would need to know where it is entering the wall to be able to better assess a possible effect on carrying moisture and effectively on durability.

Conclusion

To design and build safe, healthy, durable, comfortable, and economical buildings, one must require a certain level of airtightness. In this context, we must require installation of AB systems. One should also undertake research to enable quantification of the effect of air leakage on thermal performance of the building enclosure.

AB systems are needed in the design of building enclosures in all climates. Requiring AB continuity likely draws more care to both design and construction of these systems. As far as proposing airtightness criteria, we realize that criteria should be rather a benchmark or a range related to both energy efficiency and durability. This would make airtightness criteria practically related to climate and building type and size. Nevertheless, in the process of ensuring construction quality, all buildings should have mandatory requirement for performing airtightness testing during the construction. While national standards should establish airtightness level adequate such that it would eliminate large holes in the building enclosures, the smaller buildings and those located in cold climates may have much higher requirements.

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