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CBD 23

Air Leakage in Buildings

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A. G. Wilson

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Air leakage has a number of important implications in relation to the performance of buildings. It occurs through cracks and openings in windows, doors, walls and roof. Its extent depends on the design and condition of the building enclosure, the quality of materials and workmanship and the air pressure differences acting across the cracks and openings. Air leakage into buildings is called infiltration and leakage outward, exfiltration.

The relative humidity in most heated buildings in Canada is uncontrolled and depends largely on the over-all rate of infiltration. This subject is discussed in CBD 1. In buildings without mechanical air supply systems air infiltration provides the air changes required for ventilation and may also, be a source of contaminants such as smoke, soot and dust. As air infiltration increases the heating load in winter and the cooling load in summer, a good estimate of infiltration is required for the proper sizing of heating and cooling equipment. Windows and doors are the major source of air infiltration in most buildings and will usually determine the importance of air leakage in relation to heating and air conditioning.

One of the most important aspects of air leakage in relation to the Performance of Canadian buildings is the extent to which it is responsible for serious condensation problems. Unfortunately this is largely unrecognized in the design and construction of many buildings, and even when failures develop the source of moisture is often incorrectly identified. To appreciate this and other implications of air leakage, air leakage characteristics of cracks, distribution of pressure across the building enclosure and the resulting pattern of air flow must be understood.

Air Leakage Characteristics. The flow of air through openings in a structure follows laws similar to those describing air flow through orifices and capillaries. Flow through a capillary is directly proportional to the pressure drop across it; flow through an orifice is proportional to the square root of the pressure drop. The relationship for building openings or cracks falls between these limits; the flow rate also depends on the effective area of the openings perpendicular to the direction of flow.

Flow through a single opening of uniform cross-section large in relation to its length can be approximated from the relationship for a sharp-edged orifice: $Q = 2400\,A\,\sqrt{h}$, where Q is the air flow in cubic feet per minute, A the area in square feet and h the pressure difference in inches of water. For complex openings such as cracks around windows and doors or cracks in walls air flow relationships must be determined by test. Air leakage around windows is often given in terms of the length of the crack around the perimeter of the sash; in a masonry or frame wall it may be related to the over-all area of the wall. Expressing leakage in terras of the equivalent area of a simple square-edged orifice sometimes provides a useful yardstick for comparing the air leakage characteristics of different components of a structure (Table I).

Table I - Equivalent Orifice, Areas, sq. in.

13-inch porous brick wall, no plaster, 100 sq ft	3.1
Wall as above, 3 coat plaster, 100 sq ft	0.054
Frame wall, wood siding, 3 coat plaster, 100 sq ft	0.33
Door, tight fitting, 3 by 7 ft	7.6
Window, double-hung, loose fitting, 3 by 4 ft	4.7
Window, double-hung, loose fitting, 3 by 4 ft	0.93

Pressure Differences. Differences occur in air pressure between the inside and outside of buildings because of the effects of wind, temperature differences between inside and outside, and sometimes as a result of the operation of mechanical ventilation and exhaust systems.

Air flow around and over a building causes variations in pressure around it. Distribution of pressures over building surfaces depends on wind speed and direction, height and shape of the building, and surrounding terrain. In general, pressures are positive on the windward side resulting in infiltration, and negative on the leeward side resulting in exfiltration. Pressures on the remaining sides may be negative or positive, depending on the angle of the wind. They are generally negative over roofs except on the windward side of steep ones.

Pressures over the surfaces of buildings are related to the velocity head or stagnation pressures of wind. For air at standard density, the relation between velocity head and wind speed can be expressed as $p_v = 0.000482\ V^2$, where p_v, is the velocity head in inches of water column and V is the wind velocity in miles per hour. Values of the stagnation pressure for winds from 5 to 25 mph are given in Table II.

Table II - Stagnation Pressures

Wind Speed, mph	p_v, in. water
5	0.012
10	0.048
15	0.104
20	0.193
25	0.301

For buildings of simple rectangular shape, pressures might vary from plus 0.5 p_v to 0.9 p_v on the windward side and from minus 0.2 p_v to minus 0.7 p_v on the leeward side. Pressures on the other sides parallel or at small angles to the wind direction may vary from. minus 0.1 p_v to minus 0.9 p_v. Pressures over flat or low pitched roofs may range from minus 1.0 p_v at leading edges to minus 0.2 p_v over other areas. Greater values of suction may occur in small localized areas.

Inside buildings pressures due to wind action depend on the resistances to flow of cracks and openings in the building exterior and to their location in relation to wind direction. Inside pressures must adjust so, that inflow equals outflow. With openings uniformly distributed around the walls the inside pressure might range from plus to minus 0.2 p_v. If most of the openings occur on the windward side, inside pressures will increase, approaching the values on the outside. The converse will occur when most of the openings are on the leeward side.

The selection of pressure differences across building walls for calculations involving air leakage is further complicated in that the relationship between recorded wind and wind at a building site varies and is difficult to establish. Maximum instantaneous rates of air leakage are usually not important. Instead, maximum average values that prevail over several hours or longer during extremes in outside temperature are often what is required. Thus wind speeds in excess of 25 mph are usually not significant in air leakage problems.

When the temperature in a building differs from that outside, pressure differences occur between inside and outside as a result of difference in the density of the air. This is called chimney or stack effect, since it is the same mechanism that causes a draft in a chimney. With inside temperature higher than that outside, chimney effect produces a negative inside pressure relative to outside and infiltration at lower levels, with a positive pressure and exfiltration at higher levels. The opposite occurs with inside temperature lower than that outside.

When no other pressure forces are acting there is a level, sometimes called the neutral zone, at which inside and outside pressures are equal. The difference in pressure between inside and outside can be expressed as

$$p_c = 7.6\,h\left(\frac{1}{t_c + 460} - \frac{1}{t_i + 460}\right)$$

where p_c is the theoretical pressure difference due to chimney effect in inches of water column, h is the distance from the neutral zone or effective chimney height in feet, and t_c and t_i are outside and inside temperatures in °F. Selected values of p. are given in Table III; the value of p_c for other heights is in direct proportion. Thus the location of the neutral zone in a building is important in relation to air leakage since it determines the pressure difference at all other heights.

Table III - Pressure Difference Due To Chimney Action (Effective Height = 100 ft)

Temperature Difference, °F	p_c
20	0.055
40	0.115
60	0.179
80	0.250
100	0.326

If the building bas no space separations, or if their resistance to flow is small, air entering at lower levels can pass vertically through the building unhindered; the location of the neutral zone will depend -only on the resistances and vertical distribution of openings in the enclosure. If these openings are uniformly distributed vertically the neutral zone will be at mid-height of the building. If the floors are isolated from one another, however, each will have a separate chimney effect and neutral zone level with respect to outside, so that the distance of any opening from the neutral zone will be less than the distance between floors. Pressure differences due to chimney effect will never be very great under these conditions.

On the basis of a few measurements made in large multi-story buildings, it appears that the separation between floors is usually not effective in preventing air flow vertically through a building and that the pressures across the enclosure are affected by the chimney action of the building as a whole. In such buildings, neutral zone levels under winter conditions are likely to be between 1/3 and 2/3 the height of the building.

Since the neutral zone in winter is the level below which infiltration occurs and above which exfiltration occurs, any openings through which air is exhausted will raise the neutral zone level. Measurements on houses indicate that the neutral zone is probably well above mid-height owing to the flow of air up the chimney and into the attic through partitions, ceiling electrical fixtures and around plumbing stacks.

The actual pressure difference across cracks and openings and the resulting pattern of air leakage depends on wind and chimney action combined and on the effects of air supply and exhaust systems, where present. Pressure differences are approximately the algebraic sum of the separate effects. For example, when wind is superimposed on chimney action in a multi-story building, infiltration at lower levels is increased on the windward sides and decreased on leeward sides. The relative importance of wind or chimney action will depend on the type of building, local climate and on the, particular air leakage problem involved. In most parts of Canada chimney action is continuous throughout the heating season and results in a consistent pattern of infiltration and exfiltration, whereas wind is usually intermittent and results in a variable pattern of air leakage because of changes in direction.

Air Leakage and Condensation. Condensation in walls and roof construction from the flow of water vapour by diffusion under a vapour pressure difference has received much attention during the past 25 years. It is now common practice to provide vapour barriers in house construction (see CBD 9), and similar practices are now usually followed in constructing other types of insulated buildings. The extent, however, to which moisture can be transferred as a component of air flowing through cracks and joints in materials as a result of air pressure differences is not often appreciated. One aspect of this, condensation between panes of double windows, is discussed in CBD 5; such condensation is due almost entirely to moisture carried with air flowing from inside to outside through cracks around the sash. This is confirmed by observation of actual buildings, where severe condensation may occur between panes on windows at upper levels although not at lower levels. Exfiltration of air above the neutral zone is the source of moisture. Similarly, condensation between panes is more excessive on leeward than on windward sides of buildings.

Condensation can also occur in hidden parts of walls or roofs as a result of air exfiltration through cracks, openings and porous construction. The extent of such condensation in heated buildings depends primarily on indoor humidity, outdoor temperature and on the rate and duration of air flow. Exfiltration induced by chimney action and by wind from the prevailing direction is thus particularly significant in this respect. Condensation problems associated with air leakage in heated buildings will be most prevalent in upper floors, especially on leeward sides; and will increase with increasing severity and duration of winter weather and with increasing building relative humidity.

Several cases of severe wall deterioration caused by exfiltration in multi-story buildings have recently come to the attention of DBR/NRC. With increasing humidification of buildings such problems will increase. Some of these cases have resulted from cracks between window frames and the structure, particularly at the sill and head, and cracks that develop between the structural frame and nonbearing masonry walls, as below spandrel beams and especially under parapets. A system of caulking or jointing to eliminate such cracks should be provided. Severe moisture problems have also been traced to air leakage through unplastered masonry, e.g., walls of penthouses and elevator shafts, and wall construction hidden by suspended ceilings. Table 1 shows that plastering of masonry walls greatly increases air-tightness.

Air leakage into roof arrangements with an attic or air space above an insulated ceiling, as is common in houses, can result in serious condensation problems. Condensation control in houses is usually achieved by ventilating the attic with outside air. In large multi-story buildings, however, air pressure differences from chimney action are much greater and natural ventilation of roof spaces more difficult, thus requiring a different approach to roof design.

Chimney action between a heated building and a vertical air space incorporated in walls can develop in the same way as that between the building and outside. When such a space is connected to the inside of the building by cracks or openings at two levels, air can flow into the space at the upper level, deposit most of the moisture it contains and flow back into the building at the lower level. This happens with double windows with tight outside sash, furred spaces around columns or vertical risers in outside walls. Air-tightness between such spaces and the inside of the building is required to prevent condensation.

Significant air pressure differences caused by chimney action exist across the walls of cold storage buildings in summer or across cold rooms in heated buildings. Many of the condensation problems in such buildings originate with the infiltration of surrounding warm humid air through cracks in the upper part of the cooled structure; a corresponding exfiltration occurs through cracks in the lower part. The need to preserve air-tightness in such buildings by an unbroken vapour and air barrier completely enveloping the structure cannot be over-emphasized.

Effect of Supply and Exhaust Systems. Buildings are sometimes pressurized by a substantial, excess of supply over exhaust air. The purpose of such pressurization is to reduce infiltration, presumably to overcome drafts and prevent the entry of dust. The amount of excess air required to achieve a given degree of pressurization will depend on the airtightness of the structure. Any excess air beyond the equivalent of outdoor air required for ventilation will increase the heating or cooling costs of the buildings. To achieve significant pressurization, e.g., equal to the velocity pressure of wind at 10 or 15 mph, the building must be unusually air-tight.

Pressurization sufficient to overcome pressure differences from chimney action at the lower floors of tall buildings requires a total outside air supply much in excess of the infiltration that will otherwise occur, unless the various floors can be effectively isolated from one another. Pressurization magnifies condensation problems that result from exfiltration of air and the practice is of doubtful merit in most Canadian climates. Instead, more attention should be given to increasing the air-tightness of the warm side of buildings. In general, humidified buildings should not be pressurized, and provision of a small suction in such buildings might be advantageous if condensation problems are anticipated.

Conclusion. Air leakage affects building performance in several ways and each should be considered in design and construction. Heating load and building relative humidity in winter are affected by over-all air infiltration and ventilation rates. Since windows and doors usually represent the major source of air leakage in buildings, significant reductions of overall air infiltration are achieved principally by increasing the air-tightness of these components. Reduction of the air infiltration rate through windows, however, will not reduce exfiltration through other cracks and porous construction.

To overcome condensation problems resulting from exfiltration, cracks and porous construction must be eliminated on the warm side of the structure. It may be desirable, sometimes, to provide venting around the outer cladding so that moisture entering the construction from inside will be more readily dissipated to the outside. The air-tightness of the inner part of the enclosure must always be many times greater than that of the outer cladding. This is especially important in buildings that are humidified. In multi-story buildings air flow between floors should be restricted to reduce pressure differences resulting from chimney action.