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Handegord, G. O.

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AIR LEAKAGE, VENTILATION, AND MOISTURE CONTROL IN BUILDINGS

by G.O. Handegord

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SOMMAIRE

Bien qu'elles soient une cause majeure des problèmes de condensation et peut-être un facteur favorisant la pénétration de la pluie, les fuites d'air ont toujours été considérées comme un moyen acceptable d'aération des bâtiments. Malgré l'accent récemment placé sur les économies d'énergie, incitant à rendre étanches les bâtiments, beaucoup pensent encore que, à un certain degré, les fuites d'air sont indispensables et qu'il faut en tout premier lieu chiffrer les pertes d'énergie auxquelles elles donnent lieu.

On étudie dans le présent document les effets possibles du vent, des cheminées, des évents et des ventilateurs sur les fuites d'air, ainsi que l'influence de l'emplacement et de l'importance des fuites sur le profil de la circulation de l'air dans les bâtiments. On se penche par la suite ... s de condensation e... odes de limitation ... de l'humidité a... de techniques de... mes d'étanchéité ... en d'économiser ... et par prolongat...

MOTS CLÉS :

G. O. Handegord[1]

Air Leakage, Ventilation, and Moisture Control in Buildings

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ABSTRACT: Air leakage through the building envelope traditionally has been regarded as an acceptable means of ventilation, although it is a major cause of condensation problems in buildings and can be a contributing factor to rain penetration. Recent concern for energy conservation, promoting the need for air tightness, is still clouded by the notion that some leakage must be provided and that the primary effort must be toward quantifying the resultant energy loss.

This paper discusses the possible effects of wind, stack effect, vents, and fans on air leakage, and the influence of air leakage openings and their location on the pattern of air flow through buildings. The possible extent and location of condensation in relation to these patterns is considered, as well as methods of controlling moisture entry and removal of accumulated moisture. Effort toward the development of construction details, techniques, and standards to ensure air tightness in buildings and building components is advocated as the primary means of achieving energy conservation through improved building performance and extended service life.

KEY WORDS: air leakage, moisture, humidity, condensation, vapor diffusion, heating systems, chimneys

Water vapor moves from inside buildings in winter by both diffusion and air leakage into exterior walls, ceilings, and roofs to condense as water or frost on the colder, outer elements. Melting, collection, or absorption and refreezing can result in deterioration or displacement of exterior masonry components. If this moisture is not removed by drainage or evaporation it can contribute to paint failures on exterior cladding, corrosion of metal connectors or cladding, or subsequent decay and deterioration of organic materials in milder weather.

The provision of a vapor barrier as a membrane or interior coating, even if incomplete, can limit to acceptable levels the rate of diffusion of water vapor

[1]Coordinator-Building Technology, National Research Council of Canada, Division of Building Research, Ottawa, Ontario K1A OR6, Canada.

under a vapor pressure difference, but any existing or subsequent cracks, fissures, or holes in the vapor barrier or interior cladding will allow much greater rates of moisture transfer and accumulation under an air pressure difference. This can be controlled best by ensuring in design and construction that such air leakage openings are avoided wherever possible and that any joints or locations where cracks or holes are likely to develop are covered and sealed in such a way as to preserve the air tightness of the detail.

Indoor Humidity Levels in Buildings

The moisture content of the air inside any heated building in winter generally will be higher than that outdoors owing to the unintentional addition of moisture by the occupants and the operation of moisture producing equipment. The actual level of humidity will depend on the balance between the rate of moisture supplied and the rate of moisture lost by diffusion, air leakage, ventilation, and condensation.

Values for the rate at which moisture is supplied by the occupants and equipment can be estimated [*1,2*].[2] The moisture lost by diffusion will depend on the water vapor permeance of the building envelope and the vapor pressure difference across it. The moisture lost through air leakage will depend on the air pressure differences across the envelope and the size, location, and characteristics of the leakage openings through the building fabric. Losses due to ventilation will depend on the performance characteristics of vents, fans, and air-handling systems in the building and on the way in which they are operated. The dehumidification effect due to condensation on cold surfaces exposed to the building interior normally will be small, and will either be eliminated by improved thermal design of the enclosure element or by intentional lowering of indoor humidity.

Lowering of indoor humidity to minimize surface condensation on windows is one approach, but increasing the surface temperature of the window by improving its thermal properties through multiple glazing is a more satisfactory solution as far as energy conservation and occupant comfort are concerned. Simply lowering the indoor humidity to avoid concealed condensation on the exterior sheathing or cladding of an insulated construction is not likely to solve the problem nor satisfy the occupants. The temperature of the exterior sheathing and cladding of the building envelope will be close to outside air temperature if even small amounts of thermal insulation have been used. Lowering the indoor dew-point to this level to avoid condensation on such surfaces would result in most cases in indoor relative humidities of less than 10 percent.

The levels of relative humidity that are maintained in heated buildings usually will be determined by the requirements of the occupants, but in some

[2]The italic numbers in brackets refer to the list of references appended to this paper.

instances may be limited by visible condensation on surfaces exposed to the occupied space. If improved thermal performance of the envelope component in question is not possible, intentional sources of moisture such as humidifiers should be discontinued. If this does not suffice, moisture removal systems should by considered. These might well involve dehumidifiers rather than increased ventilation rates if energy conservation is to be achieved.

Humidity Levels in Houses

The moisture levels in houses in winter normally will be maintained by the occupants up to the point where excessive window condensation is experienced. In houses without chimneys, such as electrically heated houses, the input from the occupants' normal activities may be sufficient to raise humidities above such values. In fuel-fired heating systems, however, the ventilation rate afforded by the chimney in conjunction with air inlet openings normally will be sufficient to maintain relative humidity levels below the window condensation point, particularly if multiple glazing is utilized.

Relative humidities up to 40 percent can be maintained without excessive window condensation on double-glazed windows with outside temperatures down to −18°C and on triple-glazed windows with outside temperatures to −30°C. In both instances some condensation may appear around the edge of the window perimeter, but it should disappear on a warming trend. Multiple glazing selected on the basis of the outside design temperature should ensure that the window will remain clear most of the time. This criterion might well be used to judge whether to install double or triple glazing to maintain the desired humidity or whether to reduce humidity to avoid condensation during the coldest periods. [*3*].

Control of Indoor Humidity in Houses

The most direct approach to lowering indoor humidity is to eliminate or reduce obvious sources of moisture such as humidifiers, attached greenhouses and open sumps. Exposed soil surfaces in crawl spaces or cellars can release significant amounts of moisture and should be covered with polyethylene film or other durable moisture resistant membranes held down by sand, gravel, or other suitable means.

The occasional opening of windows and doors or other short-term ventilation procedures may lower the humidity momentarily, but it probably will rise to its original level as soon as ventilation is discontinued. Materials such as wood, fabrics, paper, and rugs absorb water vapor from the air until their moisture content is at equilibrium with the relative humidity. This is a slow process but it involves substantial quantities of water if all the materials involved are considered. If the relative humidity is reduced, the absorbed moisture slowly evaporates from the material, but it may take several days or even weeks before a new, lower moisture content is established. This is the reason for higher "natural" relative humidities in houses in autumn [4].

It is not likely that windows and doors will be held open very long in mid-winter because of the discomfort from cold drafts entering the occupied space. If windows are only "cracked open" discomfort may be reduced, but condensation and icing may occur, and the window may become inoperable. For these reasons windows and doors are not always a satisfactory means of ventilation in very cold weather.

Houses with fuel-fired, forced warm-air systems can utilize an outside air intake duct with an adjustable damper for continuous ventilation as required. The chimney acts as an exhaust outlet for indoor air as well as for the products of combustion. It is advisable to operate the furnace circulating fan continuously with this intake duct arrangement in order to control the distribution of outside air entering the system. A manual or an automatically controlled damper in the outside air duct can be installed. The duct should be insulated to avoid condensation on its surface in cold weather.

Although this system of ventilation can be very effective in controlling humidity levels, it involves an expenditure of energy to heat the additional outside air required for humidity control, and is therefore not energy efficient. With closed combustion or condensing furnaces, heat recovery systems in which the air being exhausted from the house is used to heat the incoming air can be employed. Domestic dehumidifiers also can remove moisture from the room air without loss in heat energy, but their moisture removal capacity may be limited at relative humidities below 40 percent because of evaporator coil frosting.

Condensation in Wall and Roof Spaces of Houses

The higher moisture content of air within heated buildings in winter provides a vapor pressure difference that causes water vapor to diffuse through the interior cladding materials towards the outside. Incorporation of a vapor barrier membrane in the construction or the application of coatings of moderate to low permeance to the exposed wall and ceiling surfaces can reduce this rate of flow considerably. A much more significant flow of moisture will occur through cracks, fissures, and holes in the construction owing to an outward air pressure difference caused by wind, stack effect, chimneys, or mechanical air-handling systems.

There has been a general tendency to assume that leakage through the building enclosures occurs primarily at doors and windows where visible joints occur. Studies undertaken on six houses in Ottawa, Canada, have demonstrated that the leakage openings contributed by windows and doors constitute only about 20 percent of the total [5]. Leakage cracks and openings in walls and ceilings are not so obvious as those around windows, but they are more numerous and constitute a higher percentage of the total leakage openings in most houses. Measurements indicate that as much as 70 percent of the total leakage openings occur in walls and that about as much can occur through the ceiling, depending on the particular house. Measurements of the area of holes in upper plates used for wiring or plumbing suggest that these may contribute about one half of the total through the ceiling and that an equivalent leakage area may develop from shrinkage of the upper wall plates after construction. Substantial leakage openings also may occur as a result of wood shrinkage or cantilevering of floor constructions at the foundation wall or second floor level, and where chimneys or plumbing stacks penetrate wall or roof construction. Poorly fitted nonweatherstripped attic access hatches are also likely locations for air leakage. Unsealed joints in ductwork and at duct penetrations or exhaust fan openings are also common, and in the extreme case fans may be incorrectly installed, discharging directly into the attic space.

Not all cracks and openings in existing houses can be sealed, nor will it be possible to ensure absolutely tight construction in new housing. But every effort should be made to provide as tight an enclosure as possible in order to reduce the rate of air leakage and minimize the amount of condensation that occurs in walls and roofs. Such measures will make it possible to control ventilation and energy loss.

Air Leakage in Houses

The direction and rate of air leakage through cracks and holes depends on the direction and magnitude of the air pressure differences created by natural forces such as stack effect and wind and by the action of chimneys, fans, and blowers. Most significant and least recognized is the stack effect due to the difference in temperature between inside and outside air in winter.

Warm inside air is lighter and more buoyant than cold outside air and tends to rise and flow outwards through cracks and openings in the upper walls and ceilings of buildings. As it leaks outward, the warm inside air encounters progressively colder surfaces, eventually contacting those below its dew-point temperature so that condensation takes place. The magnitude of the pressures will depend on the height of the heated space and the inside-to-outside temperature difference.

Air pressure differences created by wind may be of the same order of magnitude as those from stack effect for low buildings in cold climates. Pressures due to wind will act inward over the height of windward walls and outward over leeward walls and those parallel to the wind. Although suction pressures generally will be created over all flat or sloped roofs, the sustained pressure difference across the ceiling in a ventilated roof space will tend to balance out near zero.

For electrically heated houses or others with no operating chimney the mid-winter pattern of pressure differences from a combination of average wind and stack effect will probably be similar to that shown in Fig. 1. Outside air will leak inward through windward walls and room air will leak outward through the ceiling and leeward walls. The pressure acting upward across the ceiling will be due primarily to stack effect, and will act in this direction as long as the inside temperature is higher than that outside. There thus will be a constant pressure acting to move moist indoor air up into cold roof spaces.

This upward air pressure difference is counteracted and may even be reversed by the action of the burner and chimney in houses with fuel-fired heating systems [*6*]. The stack effect of an operating chimney is greater than that of the house because the flue gases are at a much higher temperature. The chimney thus acts like an exhaust fan, lowering the air pressure inside the house. The pressure difference across the ceiling therefore is reduced or reversed and the pressure difference acting inward is increased, acting over a greater total area of inlet openings, as indicated in Fig. 2. The total air change rate is thus increased, with most or all of the room air exhausting through the chimney with the flue gases rather than into the cold wall and roof spaces.

The furnace chimney represents the most significant difference between electrically and fuel-fired heated houses as far as air leakage and indoor humidity levels are concerned. The chimney provides an exhaust system when the furnace is operating and an air exhaust opening when the burner is off.

Electric dehumidifiers provide a more energy efficient method of reducing the humidity level than ventilation and may be particularly applicable in

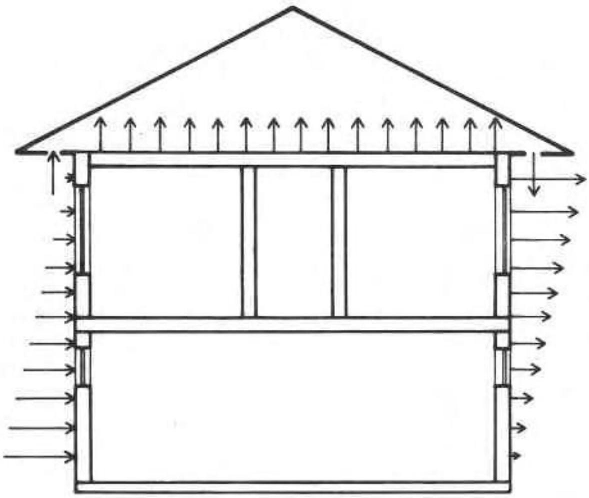

FIG. 1—*Pressure differences in houses without operating chimneys.*

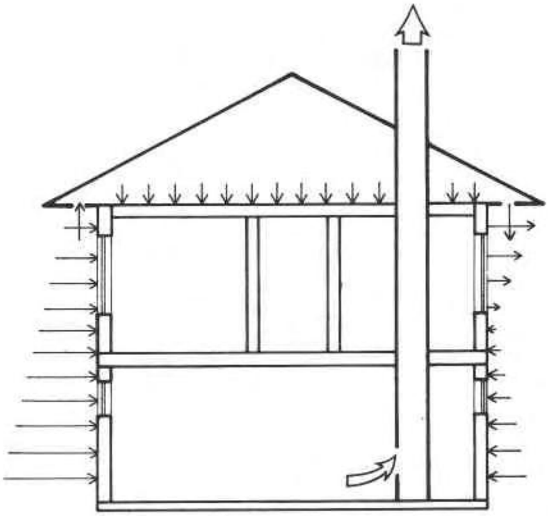

FIG. 2—*Pressure differences in houses with operating chimneys or exhaust fans.*

houses with electric baseboard heating systems. If problems of roof space condensation are experienced, however, simply lowering the humidity may not be sufficient. If the house has been tightly built, or if it can be brought up to such a standard, a relatively small capacity exhaust fan will be capable of reducing the pressure difference across the ceiling and the flow of moist indoor air into the roof space, If the house has a substantial number of inaccessible leakage openings, a larger capacity fan will be required. This will result in increased energy consumption to warm the replacement air leakage into the house. Recovery of the heat in the air being exhausted could partially balance this loss while still maintaining the desired negative pressure in the house. A small heat pump or adapted dehumidifier or air conditioner could be used to recover heat and moisture from the exhaust air.

Concealed Condensation in Larger Buildings

Buildings for human occupancy are usually humidified to a level of 30 to 50 percent to satisfy the occupants. High-rise buildings that experience substantial pressure differences as a result of stack effect and high wind pressures must be built to higher standards of air tightness than houses if energy conservation, comfort, and condensation control are to be achieved.

Air leakage through hollow concrete masonry walls is often much greater than normally assumed. Upward leakage in the cavity is not always adequately blocked and parallel random air flow passages occur between gypsum wallboard finishes and the block face.

In commercial buildings the application of rigid insulation and built-up roofing above the roof deck results in fewer openings from the interior of the space into the roof/insulation system, but a critical location for air leakage and condensation in such buildings is at the junction of the wall and roof [*7,8*]. This may be aggravated further where dropped ceilings are provided for service spaces and the exterior wall above the ceiling is left unplastered or inadequately treated with respect to air tightness. In some instances vertical service shafts provide passages for unrestricted air flow to this critical location or into exterior walls.

Air leakage through exterior walls also can occur where the structural system or services penetrate the air barrier, or where joints between dissimilar materials or components occur. Masonry cannot be installed tightly against structural steel columns and beams. In some cases subsequent installations of anchors for precast cladding have left major holes through the wall [*7*].

In principle it is preferable to have the structural frame of a building inward and separate from the exterior wall system. The wall can then incorporate a continuous structural air barrier protected from the fluctuating conditions of the weather by insulation on the outside [*9*]. Exterior cladding is best applied following the two-stage weather-tightening system to control rain penetration [*10*]. Consideration also should be given to providing access to the interior wythe and air barrier for maintenance of the air seal and joints.

The deterioration of exterior structural elements of a building and damage to the interior through air leakage and condensation have an important bearing on maintenance costs.

There is also merit in improving the air tightness of internal floors and partitions, particularly in high-rise buildings. This will tend to redistribute the total pressure differences due to stack effect so that the pressure difference acting across the exterior wall on each floor is reduced [*11*]. Such an approach also will allow better control of the air distribution within the building. It also should make it much easier to control smoke movement in buildings during a fire, and permit a more equitable apportioning of energy charges for space heating from unit to unit in apartment buildings.

The degree of tightness attainable may well have economic limits, but there is considerable evidence that many of the leakage openings existing in actual buildings result from holes cut either accidentally or deliberately in an already reasonably tight membrane or component. A specific example is the penetration of services through specified air or vapor barriers or solid components. Other leakage openings in the exterior enclosure elements result from changes in the dimensions or deflection of materials that may well be promoted by either improper location within the wall or inadequate provision of appropriate sealants or membranes to bridge the joints or cracks that eventually open up in the construction [*12*].

Removal of Condensed Moisture

With requirements to maintain reasonable relative humidity levels inside buildings in winter and the difficulty of obtaining a complete air and vapor barrier, some condensation inevitably will occur. In walls, drainage by gravity can provide the most effective means of removal, and all cavities should be drained and flashed to the outside. Some consideration should be given to carrying the flashing through to the vapor barrier if optimum moisture control is desired. Reversal of the temperature gradient due to solar heating can result in water vapor migration inward from absorptive cladding or sheathing materials or insulations in winter and resultant condensation on the outer face of the vapor barrier or interior cladding. The alternating migration and condensation will act to dry out the construction gradually if the condensed moisture is allowed to drain to the outside.

Sloped roofs over attic spaces have several advantages over flat roofs in wood frame construction. The water vapor that flows upward by air movement or diffusion through openings in the ceiling has an opportunity to mix with the attic air and be exhausted or to condense in a more uniform pattern over a large roof sheathing area. In flat wood frame roofs the condensation will form immediately above the leakage opening in the ceiling vapor barrier, and on melting will drip from low points of the sheathing to find its way into the house by virtue of the openings through which it passed upward initially. In cathedral ceilings localized condensation also will occur near leakage openings, but it can drain to outside at the soffit on top of a vapor barrier that has been applied to the slope in overlapping shingle fashion.

Ventilation of roof spaces with outside air can provide an auxiliary means of removing moisture by evaporation, but it becomes less and less effective at low temperatures because of the small vapor pressure differences involved. Although increased roof sheathing temperatures and increased potential for sublimation and evaporation result from solar radiation, attic or roof space ventilation is most effective at milder outside temperatures. In some cases where leakage openings in the ceiling vapor barrier cannot be sealed or reduced in number, closure of roof space vents and pressurization of the roof space in cold weather could be considered [*13*].

Ventilation of wall cavities may be a less effective means of removing moisture than drainage but can provide added capability for evaporation of accumulated moisture in mild weather. Circulation of outside air through porous insulation, through joints in the insulation, or through spaces between the insulation and interior cladding or structural components, however, can result in a significant reduction in thermal resistance and even in cooling of interior surfaces below the indoor dew-point. The provision of weep holes at the flashing at only one level in each exterior wall compartment will allow drainage and outward diffusion of moisture without promoting circulation of outside air to an unnecessary degree. With insulation having good drainage characteristics, air spaces could be eliminated as a requirement for moisture control. In any case, air tightness of the interior cladding and vapor barrier is the most effective way to avoid concealed condensation in heated buildings.

Achieving Air Tightness in Buildings

Specifications that simply call for a continuous air or vapor barrier are not likely to achieve air tightness in actual construction. Practical details must be developed that recognize the location of leakage paths, joints, and the potential location of subsequent cracks in a particular construction. These often may have to be developed for a specific building or type of construction, and may require changes in practice or construction sequence to achieve success [*12,14*]. Their presentation in three dimensional format or to show the sequence of construction may be necessary to ensure proper application.

Pressurization or evacuation tests on small buildings or localized air pressure difference tests on assembled components in larger multi-story buildings provide an extremely useful means of performance evaluation [*15,16*]. Only relatively simple tests need be made to locate leakage paths and to provide an indication of whether the designer and the builder were successful in achieving the objective. The required level of tightness might well be based on what is possible with reasonable forethought and care. Ideally, the tightness requirement should equate to the allowable rate of moisture transfer resulting from diffusion as defined in accepted vapor retarder (barrier) requirements in existing standards.

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