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MOISTURE MANAGEMENT IN BUILDINGS

by

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ABSTRACT

The moisture generated inside buildings must be removed on a fairly steady basis to avoid excessive indoor relative humidity, condensation, mold and mildew and the resulting deterioration of building materials. The moisture released in a building is dissipated by infiltration, ventilation, diffusion, cyclical absorption and desorption of moisture by envelope materials, condensation and drainage, or dehumidification, or by a combination of these processes.

This paper summarizes recent field and laboratory research on indoor moisture generation, exterior moisture sources, moisture transport, air infiltration, cyclic moisture storage and mold and mildew hazards. It also describes the effect of night setback of the thermostat and thermal bridges on condensation and mildew formation. The various methods available for discharging the water vapor generated indoors during the winter and their effectiveness are discussed. The limitations of infiltration and natural ventilation processes as vehicles for moisture removal and controlling indoor relative humidity are evaluated.

Recommendations are made for research projects, guidelines and standards that are needed to place moisture management in buildings on a more rigorous engineering basis.

INTRODUCTION

Moisture is generated indoors in most types of buildings. This moisture release causes a higher average absolute humidity indoors than outdoors unless air conditioning or dehumidification equipment is used to remove the moisture. In the absence of such equipment, the moisture released in the building is dissipated in one or more of the following ways; exfiltration and infiltration, natural or mechanical ventilation, diffusion through the building envelope materials or by condensation on cold surfaces with incidental or planned drainage.

Thirty years ago when the techniques of air infiltration measurement were in their infancy, it was generally believed that the diffusion of indoor moisture into building envelopes [1] was the principal cause of hidden condensation and the resulting deterioration in the walls, ceilings and roofs of buildings. Based on this diffusion concept as the cause of damage, typical building practice evolved to require or recommend condensation control measures for each major component of the building envelope that would protect it [2] from hidden condensation, without considering how the moisture generated indoors was removed.

In the last ten to fifteen years it has been demonstrated and accepted that the convection of moist indoor air accounts for the major portion of the moisture transport into the building envelope. This convection of moist air occurs at joints in the vapor retarder, around window and door frames, at joints between major building elements, and through penetrations of the vapor retarder by light fixtures, convenience outlets, ducts, grilles, plumbing pipes, access doors, etc.

The construction technology for preventing condensation in residential building envelopes resulting from diffusion and convection of indoor moisture has been developed and demonstrated, [3] but it has not been promulgated as guidelines of good practice for wide dissemination. Climate is considered to be the principal factor, winter and summer, that determines whether or not the indoor moisture in a building and/or outdoor humidity will be likely to cause condensation in the building envelope. Most current guidelines and regulations are based on this concept. However, the Residential Conservation Standards [4] of the Department of Energy (DOE) state that outdoor temperature, building size, density of occupancy, amount of moisture generated indoors, ventilation and infiltration rate, type of heating system, slope of roof, and attic and wall cavity ventilation all affect the potential for moisture condensation in the building envelopes of residences.

Currently, there is a difference of opinion about whether or not moisture condensation in building envelopes is a serious problem in the United States. Some builders and building technologists believe that most new buildings are now constructed with adequate vapor retarders, air barriers and moisture storage capacity to prevent deterioration of building envelopes from condensation, and that problem cases are likely to be in old buildingd constructed before adequate technology was known or with builders who are not applying moisture conrtol technology correctly. However, the use of greater amounts of insulation and the tightening of buildings to reduce random air leakage and to conserve energy tend to raise indoor relative humidity levels and accentuate the need for careful control of moisture diffusion and convection into the building envelope, and for a planned method for discharging the moisture generated in the building. These trends in building construction also raise important issues on indoor air quality.

CURRENT RESEARCH

Several recent laboratory, field and analytical studies of moisture transport, air infiltration and moisture generation provide a basis for evaluating or formulating various moisture management systems for buildings.

The most recent data[5,6] on the typical generation of moisture in residences dates back to the early 1970's. Living patterns have changed since that time in terms of occupancy, cooking habits and other factors, therefore, these data may not precisely represent current conditions.

Laboratory and/or field studies at Princeton University[7], Forest Products Laboratory[8], Lawrence Berkeley Laboratory[9], and Owens-Corning Research Center[10] have shown that significant adsorption and desorption of moisture occurs on a diurnal or seasonal basis in the roofs and walls of a house and that this process can influence the likelihood of condensation. Analytical modeling and laboratory validation of the attic ventilation requirements to prevent attic condensation in residences with the effect of moisture storage in roof sheathing has been carried out by the National Bureau of Standards[11,12]. More comprehensive quantified evaluation of the storage capacity in roofs and walls is needed together with guidelines on how this phenomenon can be safely used in removing indoor-generated moisture.

Recent field studies in residences[13,14] have identified the leakage of indoor air into various parts of the building envelope and the percentage of the total leakage represented by each category.A demonstration house[3] constructed by the National Association of Home Builders illustrated the construction techniques needed to provide a very low air leakage rate and to prevent condensation in the building envelope.

Studies at the Forest Products Laboratory[15,16] of various wall constructions exposed to ambient climatic conditions in Wisconsin and to selected constant levels of indoor temperature and relative humidity indicated that indoor relative humidities of 35% and 40% could be maintained indoors with little or no wall cavity condensation when vapor retarder paints and continuous polyethylene film, respectively, were applied at the interior side of the walls. These results were obtained with little convection of moist air into the wall cavity from the indoor space. Sherwood found that walls representing older homes[17] in the Wisconsin climate without a vapor retarder revealed condensation during most of the winter months when exposed to a constant indoor relative humidity of 35%.

A few field studies [18,19] in residences have indicated the extent to which a fuel-fired furnace provides ventilation in a house and thus aids in removing indoor moisture. A field study by the National Association of Home Builders[20] of relative humidities and temperatures in the attics of houses with attic ventilation showed no evidence of condensation with or without a vapor retarder in the ceiling. Since the attic ventilation rates were not measured in this study, it is impossible to determine how much moisture was removed from the attic by the ventilating air.

Two field studies[21,22] in residences have shown that mold and mildew can develop on the inner surfaces of the exterior envelope when the relative humidity at the room center was in the range from 45% to 55%. This phenomenon was due in large part to thermal bridges in the exterior envelope which produced relatively large temperature differences between the air at room center and local envelope surfaces, thus causing wall surface conditions conducive to mold growtm.

Zarling et al[23] have reported that most buildings in the sub-Arctic climate experience some form of moisture problem because of the long heating season and low outside temperatures. The authors suggest that transport of moisture into the exterior envelope must be kept at a very low level and that moisture removal by a ventilation system that incorporates an air-to-air heat exchanger is a preferred method for reducing energy requirements.

Gavin[24] discusses the models that have been developed by various researchers for describing moisture migration through composite walls by diffusion alone, by combined diffusion and convection, and by a combination of diffusion, convection and storage.

MOISTURE GENERATION

Indoor Moisture Sources. The principal indoor sources of moisture in residences are:respiration, perspiration, combustion in unvented fuel-burning appliances, cooking, bathing, laundering, house plants, and humidification if such an appliance is used. High rates of moisture generation can occur in newly constructed houses as a result of initial drying of construction materials such as wood, concrete, masonry, plaster, etc. This initial drying process takes place over several months time. Leaking water pipes can also be the source of localized wetting of portions of the building.

Data[5,6] published in the early 1970's indicate that a typical family of four persons is likely to generate 18-20 pounds of water vapor per day. Approximately half of this daily rate is due to the respiration of the occupants. The rate of moisture release in a residence is not constant during the day nor is it uniformly distributed throughout the rooms of the house. The moisture release occurs principally in the kitchen, dining room, living room, bathrooms, and laundry during the day, and principally in the bedrooms at night.

In offices, respiration of the occupants is the principal source of moisture release at a rate of about 0.1 lb/hr per person for sedentary conditions[25]. Much higher rates of moisture release can occur in commercial buildings where the occupants engage in significant physical activity or where the principal processes release moisture directly into the indoor environment. Restaurants, cafeterias,and kitchens in commercial buildings, and movie theaters, auditoriums, and indoor swimming pools are examples of building occupancies with very high rates of moisture release[26]. These classes of facilities require careful design of the ventilation system to control moisture conditions. The recommended relative humidity level in many parts of health care facilities is in the 50% to 60% range. These levels of humidity are likely to cause winter condensation in the exterior building envelope unless special care is exercised in the use of vapor retarders and air barriers, snd overrun in relative humidity is prevented.

Exterior Moisture Sources. The principal exterior sources of moisture that can enter building construction and cause deterioration are: rain (it may or may not be wind driven), melting snow, ice dams on roofs, capillary rise from the earth through foundations, water vapor released in the crawl space, outdoor water vapor in humid climates, and lawn-sprinkler water impingement.

The climatic exposure of roofs to wide temperature cycles, ultraviolet light, rain, hail and wind typically cause accelerated deterioration of roof materials and make rain leakage a prevalent problem. Rain or sprinkler water need not be wind driven to enter cracks and open joints in hygroscopic materials used in masonry walls. It was demonstrated in housing units in Pensacola, Florida[27], that hairline cracks in the exterior surfaces of masonry walls would suck in, by capillary action, drops of water that were just brought in contact with the surface. Fine wind-driven snow can enter attic spaces through open grilles or soffitt louvres during blizzard conditions in northern climates, and accumulate in sufficient quantities to wet ceilings and walls when it melts during warm spells of weather. When porous masonry foundations come in contact with the earth or extend into the earth, ground water or ponded water[28] can rise some distance up the wall by capillary action unless an effective barrier has been installed. The absorbed moisture in the lower part of the wall may dissolve salts which are then deposited near the surface when evaporation takes place both indoors and outdoors. The results of this capillary rise of water may be surface staining of the wall, peeling of paint or wallpaper, efflorescence, mold growth,and increased interior moisture load. Ground cover membranes are used in some geographical areas to minimize vapor transmission from the earth in crawl spaces to the living space above the floor. Unless vapor retarders are used, summer condensation may occur inside the exterior walls of air-conditioned buildings in the region adjacent to the Gulf of Mexico and South Atlantic coasts of the United States where outdoor dewpoints of 80°F may be sustained for fairly long periods.

Windows and doors are frequently the source of leakage of rain. Weatherstripping is typically used to provide a seal at moveable joints in window sash and around doors, but weatherstripping tends to deteriorate with age or use. Sealants and caulking are used to close joints between the framing of doors and windows and the adjacent wall materials. Sealants and caulks vary in their properties of adhesion, expansion and contraction characteristics and deterioration with age, so maintenance and replacement of weatherstripping and sealing materials are likely to be required at intervals of a few years.

MOISTURE ABSORPTION AND STORAGE

Moisture Absorption by Building Materials. Many building materials such as wood, masonry and clay units, concrete, brick, plaster, composition board,and some types of insulation have a porous structure. Porous materials can absorb water in the liquid state from condensationn or water leakage sources and can adsorb water directly from moist air as a surface layer of water molecules on solid materials. Non-porous materials such as glass, metals and many plastics can adsorb moisture as a film on their exposed surfaces, but have a negligible total moisture content.

The moisture content of common building materials has been summarized by Whiting[29] in a literature survey. Most wood species have a fiber-saturation point for water of about 30% of dry weight, but can hold additional water in cell cavities. The moisture content of saturated dense concrete is approximately 4.5% by weight, whereas lightweight concretes may have saturated moisture contents up to 68% depending on the density of the material. Moisture contents of less than 10% by volume for clay brick are representative of those actually encountered in building walls. Hardwood species[30] exhibit a shrinkage of 9-11% tangentially when dried from green condition to oven dry state, whereas the corresponding shrinkage values for softwoods range from 5-8%. Radial shrinkage is appreciably less.

The principal adverse effects of excessive moisture in building construction, sometimes accompanied by high indoor relative humidity,are : (1) decrease of thermal resistance of insulation when wet, (2) corrosion of metals, (3) undesirable expansion of building materials, (4) growth of fungus or mold, (5) leaching of salts from brick or masonry, short circuits in electrical wiring, (7) peeling of paint, and (8) discoloration of building materials. Experience, over the years, has indicated that approximately 90% of the premature deterioration in all types of building construction is caused directly or indirectly by water. Each of these adverse effects has been observed in building construction under certain circumatances.

Diurnal and seasonal movement of moisture[31] in insulated roofs can cause very high heat transmission values due to the reversal of the temperature gradient.

Temperature and moisture content differentials between the upper and lower chords of wood roof trusses can cause measurable seasonal vertical movement.

Seasonal moisture variation in the lamina of plywood sheathing can cause delamination of the plywood and strength degradation.

Summer condensation on the basement/crawl space wood support members can cause structural failure of flooring.

Alternate freezing and thawing of the exterior elements of concrete and masonry walls in cold climates can cause spalling of the surface materials.

Steel pipes and electrical junction boxes embedded in wet insulation can cause corrosion of metal and electrical short circuits.

Moisture Storage Mechanisms. Porous building materials used in building construction provide storage for a significant amount of moisture in the exterior elements of the walls, especially under winter conditions. Laboratory and field studies have already been cited indicating that this moisture storage phenomenon in walls and roofs may prevent condensation under some winter conditions.

By calculating the mass of wood in the exterior elements of the walls and roof of a frame house , it can be estimated that several hundred pounds of water could be stored in these wood members while raising a summer level of 5% moisture to a safe winter level of 20%, if the moisture absorption were uniformly distributed. However, analysis of the probable convection paths for infiltration and ventilation air through a building indicates that uniform distribution of moisture storage is improbable. Furthermore, since a family of four persons can generate about 3600 pounds of water vapor during a 6-month winter season, moisture storage can serve only as an adjunct to other moisture management processes.

The high moisture storage capacity of masonry block as an exterior wall material has been shown[27] to be a disadvantage in warm humid climates during the air-conditioning season, if cracks in the mortar joints or hairline cracks in the blocks themselves are exposed to rain. Solar exposure of the walls can drive stored moisture toward the inside of the wall as water vapor and cause condensation on the interior wall covering and increase the interior moisture load.

TEMPERATURE EFFECTS

Night Setback: Night setback of temperature in residences in which the indoor relative humidity is kept moderately high by low infiltration/ventilation rates or by humidification can increase the potential for condensation in the exterior envelope or for mold growth on the inner surfaces of the exterior walls. As pointed out earlier, most of the moisture generation in a residence at night occurs in the bedrooms. Some people close bedroom doors at night for privacy, which can reduce recirculation of air to a central furnace unless specific measures are taken for recirculation. Reducing the room temperature at night lowers the temperature of the interior parts of the exterior walls and ceiling at the same time that moisture generation is concentrated in the bedrooms, and outdoor temperature is typically reaching a minimum. These concurrent conditions increase the likelihood that diffusion and convection of moisture into the walls and ceiling could cause condensation. At the same time these conditions increase the possibilities that temperature conditions adjacent to any thermal bridges that may exist would promote mold or mildew. Thus it is important to give special attention to moisture dissipation from bedrooms during the night, especially if night setback of temperature is practiced. Similar effects may take place if the bedrooms are kept cool during the day and warm, moist air from the rest of the house reaches the bedroom areas.

Thermal Bridges: The structural members in the exterior walls, ceiling/roof construction and around windows and doors are typically composed of wood, metal or masonry. In many buildings these structural members provide a continuous path of lower thermal resistance from the exterior to the interior surfaces of the wall or ceiling/roof than other parts of the envelope. These lower thermal resistance elements produce areas of lower interior surface temperature on walls or ceiling during the winter which can increase the likelihood of mold or mildew growth if the indoor relative humidity is moderately high. Mold and mildew have been observed in residences[21,22] where the measured relative humidity in the middle areas of the room was in the range from 45% to 55%. Thermal bridges and local cold spots on exterior wall surfaces can also be produced by ducts or plumbing vents that displace insulation in the exterior wall and provide a low thermal resistance between interior and exterior surfaces.

MOISTURE REMOVAL

The moisture generated inside of buildings must be dissipated on a fairly steady basis to avoid excessive relative humidity, condensation, mold and mildew, and deterioration of building materials. In the winter time, the outdoor air typically has a sufficiently low dewpoint to act as a vehicle for moisture removal. The design task under winter conditions then is to provide an effective and economical procedure for moving outdoor air into and out of a building at a rate that will remove the moisture released indoors while maintaining the desired indoor relative humidity level.

It is not the purpose of this paper to describe the methods currently being used to protect the various parts of the building envelope from deterioration due to moisture transport and absorption.

It should be noted that the movement of outdoor air through most buildings serves many funstions, some essential and others optional. Outdoor air is almost universally used to provide oxygen for respiration of man and animals and for the combustion of fossil fuels. Although outdoor air is not always of suitable quality, it is often introduced under conditions for the following purposes:

a) to improve indoor thermal comfort,
b) to dilute the concentration of contaminants generated indoors,
c) to lower indoor relative humidity and to inhibit concealed condensation in building construction,
d) to pressurize indoor space to exclude drafts or dust. (This approach can force moist indoor air into the building construction causing major moisture problems).

Moisture will not always be the controlling factor in determining the rate of outdoor air supply. However, in buildings of dense occupancy or high indoor moisture generation, moisture removal may be the determining factor in selecting the ventilation rate.

In the two or three decades before the energy crisis in the 1970's most houses and many commercial buildings were not designed to maintain a winter relative humidity in the comfort range. In fact, as late as 1950 the building community[17] had not agreed on what constituted a desirable relative humidity in occupied buildings. Typical practice was to control the indoor temperature during the winter and allow the indoor relative humidity to drift downward, sometimes below 10%, as the weather got colder. As building designers became convinced that vapor retarders were desirable in building construction to prevent hidden condensation, some homeowners, usually in the middle or upper income brackets, began to demand indoor relative humidity in the comfort range (30 to 60 %) during the winter. During this same period the technology of air infiltration measurement was in the early stages of development and few designers knew how much air leakage was occurring in buildings.

As the cost of energy rose rapidly in the late 1970's and early 1980's, the thermal resistance of building envelopes was being increased and air leakage was being reduced, often below 0.5 air change per hour. The reduction in air leakage was accompanied by increased indoor relative humidity and greater concern about hidden condensation, thermal bridges, mold and mildew growth and indoor air quality.

The methods available in residences for discharging or managing the water vapor generated indoors during winter weather are:

a) flue exhaust from combustion equipment,
b) outdoor duct connection to furnace fan inlet,
c) exfiltration and diffusion of moisture through the ceiling to a ventilated attic,
d) limited diffusion and convection of indoor moisture into building walls combined with storage of moisture in the building envelope materials during the winter followed by natural drying during the spring and summer,
e) stack exhaust from the livimg space to the attic or roof,
f) exhaust fan under manual or automatic control,
g) dehumidification or humidification.

None of the first five methods listed above provides control of indoor relative humidity, assures indoor moisture removal to achieve a satisfactory humidity level, nor optimizes energy use relative to the moisture removal process. The use of an exhaust fan controlled by a humidistat or an automatically-controlled dehumidifier can provide a comfortable indoor relative humidity level in a reasonably tight house and be effective in energy conservation. It should be pointed out that moisture management only becomes important if the owner or occupant of a residence desires to maintain winter relative humidity levels in the comfort range and to attain reasonably low energy use in the process.

The reliability of infiltration as a vehicle for introducing outdoor air into buildings is being seriously questioned because of its variability with wind and outdoor temperature, its strong dependence on quality of workmanship, and to some degree on the living habits of the occupants. The energy cost for infiltration is as variable as the quantity of air handled. Natural ventilation under occupant control as a moisture management technique has many of the drawbacks of infiltration. The amount of ventilation provided by flue exhaust of combustion equipment and the much-used outdoor duct connection to the furnace fan inlet has only been measured in a few research situations. These methods of introducing outdoor air do not respond to the requirement for removal of an approximately constant moisture load and a desire for a controlled indoor relative humidity. Some builders believe that diffusion and convection of indoor moisture to a ventilated attic is an effective method of winter moisture management in residences. However, attic ventilation in winter is also dependent on outdoor temperature, wind velocity and direction and quality of workmanship, and serious moisture problems in the attic may be the result. The ecocomics and effectiveness of this moisture removal process has not been compared with the use of a ceiling vapor retarder and air barrier and the direct exhaust of much lesser quantities of air directly from the living space.

During hot summer weather air conditioning is the preferred method for removal of indoor-generated moisture, if human comfort is a desired objective. If air conditioning is not available for economic reasons, large amounts of outdoor air may be passed through a building to prevent excessive temperature and humidity rise above outdoor conditions. However, with whole house ventilation, good distribution of the ventilating air to all rooms and to closets is necessary to minimize mold and mildew growth in hot, humid climates. In milder warm weather, liberal ventilation of a residence by either natural or mechanical circulation of outdoor air is an economical and effective means of moisture and heat removal.

In office buildings and many types of retail stores the rate of indoor moisture generation per occupant is significantly lower than in residences. In commercial buildings the amount of outdoor air introduced into a building is often specified as a code requirement. It may be expressed in terms of air changes per hour, a percentage of the total air circulated, or in terms of the ventilation rate per occupant or per unit floor area of occupied space. Ventilation requirements expressed in these prescriptive terms do not assure a comfortable indoor relative humidity without humidification of the outdoor air nor provide economical use of energy. The thrust to conserve energy has caused extensive reexamination of the guidelines for ventilation in commercial buildings and modification of design procedures by engineers and architects.

RESEARDH NEEDS AND GUIDELINE DEVELOPMENT

The rise in cost of energy since 1974 has necessitated the use of more rigorous engineering design, greater care in building construction and increased measurement technology in the interlocking processes of building ventilation, moisture management and indoor air quality. These changes in the building process are somewhere in mid-course. More research to develop essential technical information and a great deal more cooperative effort within the building community in promulgating consensus design and construction guidelines are needed to produce buildings that provide safe and comfortable indoor air quality, to avoid premature deterioration of building materials, and to assure economical operation within the present context of human needs.

Some of the research projects and consensus guidelines and standards that would assist in stabilizing moisture management in buildings are listed below.

a) Develop new data on moisture generation in residences that reflect current living and work patterns, occupant density, family composition, and moisture-producing processes and equipment; and including time-of-day and room-to-room variations and considerations.
b) Develop a broader data base on air infiltration rates in multi-family residences and commercial buildings.
c) Determine by field and analytical research the lower limit of airtightness that should be sought in the design of residential and commercial buildings.
d) Determine the climate and use conditions, if any, for which infiltration and natural ventilation are functional and cost-effective means for supplying outdoor air to occupied buildings.
e) Conduct a comprehensive study of the potential usefulness of diurnal and seasonal storage of moisture in building envelopes as an adjunct method for discharging indoor moisture to the outdoors.
f) Conduct field and laboratory studies of thermal bridges in envelope construction to develop useful relationships among thermal resistances of bridges, climate, ventilation effectiveness,and indoor relative humidity at typical control locations.
g) Conduct definitive studies on the types and quality of vapor retarders and air barriers needed for various levels of indoor relative humidity from 30% to 60% in various climates.
h) Conduct research studies of the ventilation effectiveness of various ventilation systems in all major building occupancies.
i) Develop a consensus standard for the measurement of ventilation effectiveness in residential and commercial occupancies.
j) Conduct field studies to correlate ventilation effectiveness, health and comfort factors, and energy use in office buildings.
k) Compare the functional effectiveness and economies of removing indoor moisture by attic ventilation without a ceiling vapor retarder/air barrier, and using a ceiling vapor retarder/air barrier and much less direct exhaust of air from the living space.
l) Develop consensus guidelines for the retrofit of residences that include considerations of moisture control,air quality and energy use.
m) Develop and validate a model for the ventilation requirements of different types of buildings that takes into account infiltration, oxygen requirements, CO_2 limits,moisture control, contaminant dilution, and indoor-outdoor pressure relationships.
n) Develop a nomograph relating monthly average outdoor dewpoint, indoor moisture release / person, indoor relative humidity and ventilation rate.
o) Develop and publish consensus guidelines for control and management of moisture in buildings in a form useful to designers, builders and building operators.

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