Moisture Fundamentals and Mould

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Introduction

In industrialised countries most people spend more than 90% of their lives inside buildings. During this time the nature of the enclosed environment directly affects the health, quality of life, and productivity of the occupants.

Modern buildings, however, clearly have a problem providing a healthy or even appropriate indoor environment. The US Environmental Protection Agency (EPA) concedes that about 30% of new or renovated buildings have serious indoor air quality problems (IAQ), and ranks IAQ as our most prominent environmental problem (Roodman and Lenssen, 1995). In fact, recent estimates place the direct health care costs of poor IAQ in the US at $30 billion, with sick leave and productivity losses adding another almost $100 billion annually (Fisk and Rosenfeld, 1997).

Extensive measurements by numerous agencies have shown that many modern buildings contains a chemical soup of volatile organic compounds (VOC's) like formaldehyde, xylene, isobutylaldehyde, vinyl chloride monomer, and other organochlorides, aldehydes and phenols from all kinds of manufactured wood products, paints, carpets, and synthetic textiles including furniture and carpets, plastics, foam, tile and carpet glue, etc.

Radon from the soil, ozone from some electrical appliances, and micron-sized particles from many sources add to the health risk. The EPA and Surgeon General estimate between 5000 and 20 000 deaths per year can be attributed to radon gas in the US, where it is the second leading cause of lung cancer (Marinelli and Bierman-Lyle 1995).

Airborne particulates, especially those less than about ten microns in diameter, can seriously damage the lung. Small particles can penetrate deeper into the lung, while larger particles are filtered out by the body's natural defences.

A major concern in many cold-climate countries is the growing number of studies that link allergies, immuno-depression, and illness to the amount and type of mould or fungal growth in a building (e.g., see Health and Welfare Canada 1987, Scanada 1995). By avoiding surface relative humidities in excess of about 80% RH fungal spores, unavoidable in all buildings, will be starved of the moisture they need to survive. Mould growth within the building envelope can also affect health if an interior air barrier is not present.

This paper will emphasize the realtionship of mould and moisture an describe general moisture fundamentals required to understand and thereby control moisture in buildings.

Moulds, Fungi, and Buildings

It is estimated that there are 1.5 million species of fungi, although only about 400 species have been proven to be agents of disease in humans and animals. Fungi can be subdivided into two groups: moulds and yeasts. Moulds consist of those fungi that grow in filamentous form, whereas yeast are characterized by single cells that reproduce by budding. Since fungi do not contain chlorophyl they do not require, and in fact shun, light.

Moulds are not desirable in buildings for three primary reasons: they cause decay of materials, including structural members, they cause objectionable staining, and they can have negative health impacts. The health impacts are not completely understood, but there is no doubt that the spores given off can cause allergic reactions and are particles in the dangerous size range. Moulds also produce mycotoxins and volatile organic compounds (VOCs).

Fungal growth requires:

1. infestation,
2. nutrients,
3. temperature,
4. moisture

Infestation of a building must be assumed. Mould spores are present in the outdoor air as well as in materials delivered to construction sites. Hence, it must be assumed that if conditions for fungal growth are favourable, there are likely mould spores available.

Nutrients for fungi are also usually available in buildings. Fungi, which fundamentally require carbon and sugars, evolved over many billions of years to efficiently decompose plant and other organic matter. Many building products are organic – wood and paper, many glues and paints, etc. Cellulose has the advantage that it can be broken down into sugar. However, mould can even grow on ceramic tile since small amount of captured airborne dust, dirt and even soap provides food for the nutrients. The larger the surface area of the material, and more predigested it is, the more quickly and easily mould will begin feasting on a material. It is for this reason that the paper facing on gypsum, and the untreated cellulose in ceiling tiles provides an ideal source of food, while solid wood is not nearly as attractive.

Temperature is important for the growth of most organisms, including mould. The ideal conditions for mould growth are species dependent, but tend to be in the range of 22 to 35 Celsisus. Most moulds will grow much more slowly as the temperature drops, and few grow at temperatures below 5 Celsius. Above about 50 Celsius most species do not grow. Mould spores can survive outside of this range – from well below freezing to over about 60 Celsius. When temperature conditions return to favourable conditions, the spores will ensure that mould growth resumes.

Moisture is also necessary for all organisms. Fungi typically require a water activity of 0.80 or more to sustain growth. Water activity of 0.8 can be thought of as the equilibrium moisture content at 80% RH.

Some moulds can grow at levels down to 0.65, but these species are less important to building problems, and the growth is very slow, even on nutrient rich surfaces.

Alkalinity and radiation also play a role – most fungi require the pH of the growth substrate to remain within the bounds of about 5 to 8, but growth may still occur at pH levels of up to 10 in some cases. This sensitivity to alkalinity is the reason that lime washes and caustic soda were used in the past to control fungal growth. Both materials produce a fatal pH of 12 or more. Modern research has developed alkaline lime-based paints that are so effective they can be used in hospital ductwork. Exposure to ultraviolet radiation may slow or kill fungi, but this depends on the intensity. Exposure to natural light typically reduces fungal growth since the light warms (and hence dries) the surface and the UV intensity can be high.

Since buildings are infested with mould spores, provide nutrients to the mould in the form of building materials and dust/dirt, and are maintained at temperatures conducive to mould growth, the obvious means of controlling mould growth is to restrict the moisture available.

The remainder of this paper outlines moisture control strategies for buildings in general, and mould in particular.

Moisture Problems

Moisture is involved in almost all building enclosure performance problems or deterioration processes, and hence a general understanding is useful. These problems include:

- leakage of rain water into the building;
- freeze-thaw deterioration of concrete, stone, and masonry;
- electrochemical corrosion of metal components such as structural framing, reinforcing bars, masonry anchors, ties, flashing, etc.;
- biological, especially fungal (mould, rot, decay) growth, which can have a major effect on occupant health, structural capacity, and appearance;
- the chemical deterioration and dissolution of materials such as gypsum sheathing, wood products, and damaging chemical processes such as carbonation and alkali-aggregate reaction;
- volume changes (expansion, shrinkage) that can cause structural failure, cracking, degradation of appearance, etc.;
- discoloration (staining, 'dusting', irregular wetting, etc.) of building finishes.

For a moisture-related problem to occur, it is necessary for at least four conditions to be satisfied:

1. a *moisture* source must be available,
2. there must be a *route* or means for this moisture to travel,

3. there must be some *driving force* to cause moisture movement, and
4. the material(s) involved must be *susceptible* to moisture damage.

To avoid a moisture problem one could in theory choose to eliminate any one of the four conditions listed above. In reality, it is practically impossible to remove all moisture sources, to build walls with no imperfections, or to remove all forces driving moisture movement. It is also not economical to only use materials that are not susceptible to moisture damage or mould growth. Therefore, in practise, it is often advantageous to address two or more of these prerequisites so as to reduce the probability of having a problem.

Therefore, *controlling* moisture and reducing the risk of failure by judicious design, assembly and material choices must be the approach taken in the design of durable building envelopes.

Moisture control can be considered to be a function of three potentials:

1. wetting,
2. storage, and
3. drying.

Materials, assemblies, and environments may all be assessed by consideration of these potentials. The environments that the enclosure separates provide both the source of wetting and a sink for drying. Therefore, the wetting and drying potentials of the interior and exterior environments are just as important for assessing moisture as the same potentials of an assembly.

The relevant characteristics of an environment can be grouped together with the characteristics of an enclosure to define an overall (i.e., enclosure plus environment) wetting potential and an overall drying potential. Such potentials are necessarily climate as well as assembly specific. Therefore, the statement that "this is a durable, high performance wall assembly" cannot be taken seriously without the context of climate, e.g., is the enclosure to separate an operating room from the Antarctic winter or a living room from the Saharan desert.

For example, using a material that is not supposedly susceptible to moisture damage (e.g., good quality face brick) in locations with high wetting potential (such as at windowsills or as garden wall copings) often leads to a problem. In massive brick walls, the moisture storage capacity is so high that the moisture content of the brickwork never exceeds a performance threshold. In a drier climate, such as the Canadian prairies, the potential for drying is higher than the potential for wetting and again, the moisture content of the brickwork remains below its performance threshold. Just as for brick, understanding the moisture in materials such as wood and the time of wetness of steel can be used as a measure of their vulnerability to premature deterioration.

Complicating the assessment described above is the fact that the performance thresholds, and even what physical measures one should use to define a threshold, are unknown or poorly defined for most materials and assemblies.

The ability of a wall assembly to dry and store moisture, as well as its resistance to wetting are of great importance in assessing its vulnerability to moisture-related damage and deterioration. To develop some understanding of how and how much moisture can be removed from a wall by drainage, evaporation, diffusion, and ventilation, it is necessary to understand the fundamental behaviour of moisture in envelopes and the physics of the wetting and drying processes in general. The sources of moisture, the available storage and the mechanisms of moisture removal in building envelopes will be considered briefly below. A better, more quantitative understanding of the wetting and drying mechanisms of common building materials and assemblies in various climates is necessary to aid the quantification of vulnerablity. This can in turn be used to develop better methods of testing and designing for moisture performance.

Moisture Control

If a balance between wetting and drying is maintained, moisture will not accumulate over time, and moisture-related problems are unlikely. The extent and duration of wetting, sorage and drying must, however, always be considered when assessing the risk of moisture damage.

Most moisture control strategies tend reduce the amount of wetting by, for example, increasing air tightness and vapour resistance, reducing the volume of rain water penetration and absorption, etc. However, it has become generally accepted that most building construction will not be perfect, and thus wetting will occur. Therefore, the provision of greater drying potential and storage capacity have begun to receive more attention. These are powerful, and oft-overlooked moisture control design strategies. Finally, reducing vulnerability through intelligent design of building location, orientation, geometry, etc. is often the least expensive and best approach (although it must be considered very early in the concept stage).

The major wetting and drying processes and the moisture transport mechanisms involved in the movement of moisture into and out of the enclosure are summarised in Figure 1.

Wetting

The major sources of moisture for the above-grade building envelope, and their associated transport mechanisms are:

1. Interior and Exterior Air (Vapour) by diffusion and air leakage (convection)
2. Driving Rain (Liquid) by absorption ("wicking") and rain penetration
3. Soil Moisture (vapour & liquid) by diffusion, absorption and liquid penetration
4. Built-in Moisture (solid, liquid, vapour) not transported - stored in masonry/concrete, green lumber, construction rain/snow

(Note: moisture from plumbing leaks, sweating pipes, etc. is another possible source)

Either the transport process from the source to the material or layer wihin the building enclosure or the wetting process itself (e.g., condensation, rain penetration or absorption) is used to define the type of wetting. The transport mechanisms may be simple or a complex chain. For example, rain deposited on an exterior brick veneer will cause wetting when it is absorbed, but it may then be evaporated by solar heating (a phase change) followed by the parallel transport by diffusion and convection of the vapour inward, where is it may condense (a phase change) on an interior layer of polyethylene, whereupon it may both drain down to the bottom and be absorbed by the wood plate, and/or evaporate and be adsorbed by the wood studs.

Rain wetting by wind driven rain is usually the largest moisture source for above-grade walls. Rain deposition on one or more faces of an exposed low-rise building can easily exceed 100 kg/m^2/yr, but ranges from less than 10 kg/m^2/yr for a sheltered suburban house to 1000 kg/m^2/yr below a large window of an exposed high-rise building in Vancouver.

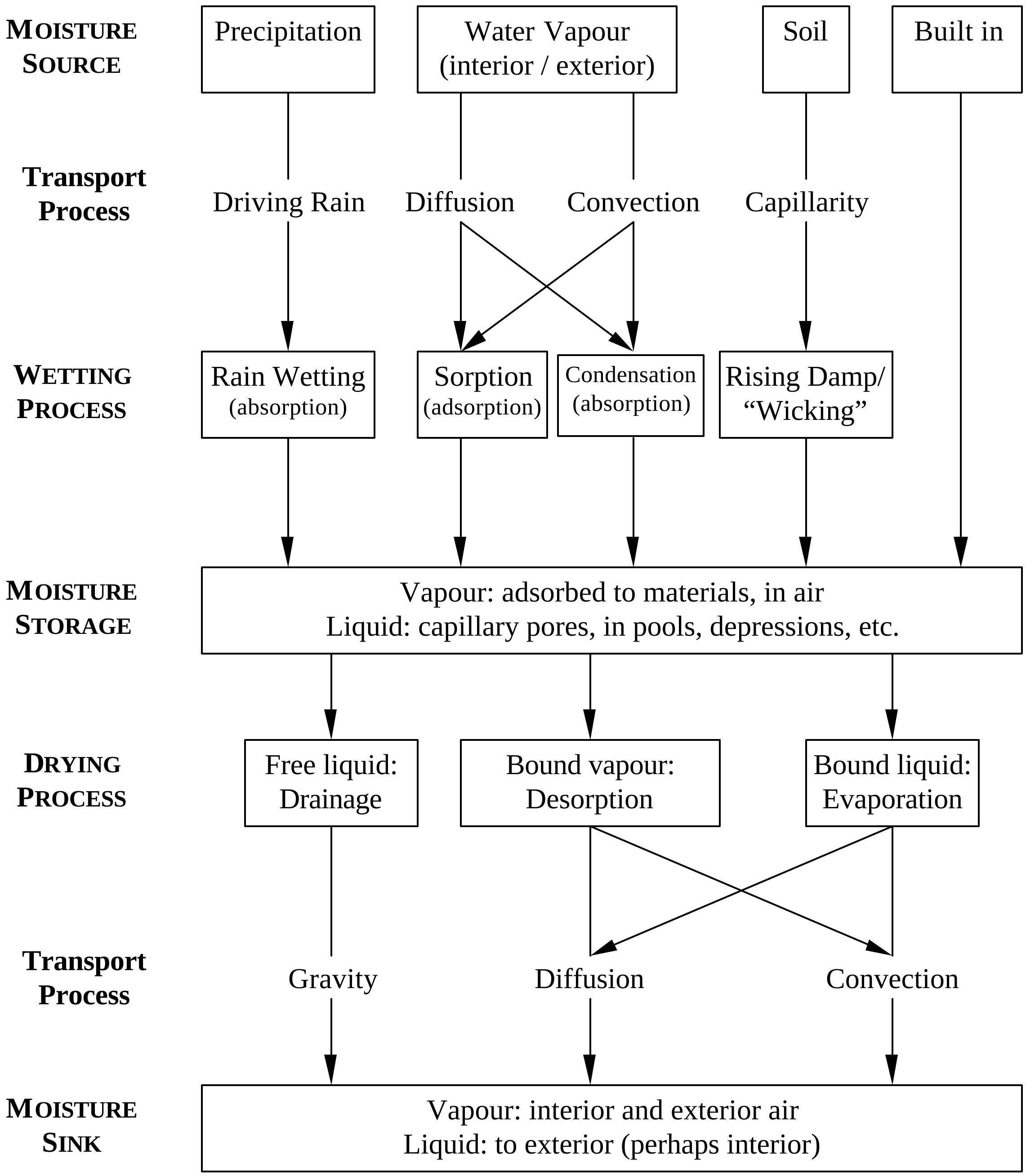


Figure 1: Wetting, drying, and moisture storage in the building enclosure

Condensation of the water vapour in exfiltrating air during winter conditions (or infiltrating air in summer conditions) can also deposit significant amounts of water within a wall. While diffusion wetting is typically not a powerful wetting mechanism, diffusion is an important means of moisture movement between layers and materials within a wall.

Although not widely known, solar heating of absorbent exterior layers (especially cladding) will often cause evaporation from the interior face of the brickwork and condensation further inside the wall assembly. These inward vapour drives are intense (several thousand Pascals) and of short duration (a few hours).

Exfiltration-induced condensation on the inner face of the exterior sheathing is another relatively common problem in cold climates which results in wetting. Because the materials used within an assembly tend to be less moisture tolerant, and the drying potential is usually much less than for outer layers, this type of wetting often results in serious performance (e.g. durability) problems. This moisture can only be removed by diffusion, ventilation, and, in extreme cases of saturation, drainage.

Built-in moisture can be important in some wall assemblies. The use of wet framing lumber, saturated concrete block, or green concrete within a wall may provide a large initial source of moisture.

Wetting by the capillary movement of water from other moisture sources (i.e. rising damp from below grade sources) is generally not a significant problem in Canada (capillarity is, however, very important as a redistribution mechanism).

Drying

An assembly's drying potential is an important factor in assessing its vulnerability to moisture problems. Moisture is usually removed from an enclosure by:

1. to the exterior by gravity drainage,
2. to the interior *or* exterior air by

- evaporation from the inside or outside surfaces,
- vapour transport by diffusion, air leakage, or both; and
- ventilation (ventilation drying).

Drainage is capable of removing the greatest volume of water in the shortest period of time. Hence it is a very important mechanism for moisture control. Provided a clear drainage path exists (e.g. cavities, slopes, drainage openings), a large proportion of rain water penetration or condensation can flow out of a wall. However, a small but significant amount of water will remain attached to surfaces by surface tension and held in materials by capillary forces even in walls with excellent drainage. Cladding or sheathing must be almost saturated by condensation before sufficient volumes of water will bead on the surface for drainage to occur. Therefore it must be assumed that water that cannot be removed by drainage will be stored within a wall.

Under the right conditions moisture not drained from a wall will dry by evaporation or desorption. The resulting water vapour can be transported out of and within the wall system either by diffusion or advection (i.e., combined diffusive and mass flow).

Diffusive drying will generally occur only in an outward direction because very low permeance polyethylene vapour barriers are located on the inside of modern walls in cold climates. Diffusion outward, especially when driven by large vapour gradients in the winter, can remove a significant amount of moisture and be an effective drying mechanism. Inward diffusive drying can occur in many climates, even cold ones, if the inner layers are sufficiently vapour permeable. The warmer and sunnier the climate the more powerful inward diffusive drying is.

Air movement (or leakage) through the envelope can, under the proper conditions, move a large quantity of moisture. While air leakage usually leads to condensation wetting under many winter conditions, it can also remove moisture. Periodic reversals of air flow from exfiltration to infiltration (when the wind changes direction for example) can allow drying even under winter conditions. Similarly, winter-time stack-effect-driven infiltration and summer exfiltration can cause drying.

Ventilation, or air flow through a space behind the cladding, uses the drier outdoor air to transport water vapour out of the wall. A recent study suggests that ventilation drying can be useful, but more research is required to quantify its benefits.

Capillary transport acts to redistribute moisture within a system. For example, water on the back of a brick veneer or wood siding will be drawn to the exterior face where it can evaporate.

The moisture in saturated exterior surfaces can evaporate to the exterior, but evaporation can take a relatively long time. Evaporation from saturated porous materials (brick, wood , stone, concrete) can remove significant volumes of moisture but its relative importance as a drying mechanism has not been quantified for Canadian conditions. Theoretical calculations, laboratory experiments, and field measurements suggest rates of up to 200 to 300 g/m^2/hr are possible although rates an order of magnitude less can be expected most of the time (e.g. when the walls are not saturated). Unfortunately, significant evaporative drying can only occur from the outside face and the remainder of the assembly will remain wet for a relatively longer time unless a well ventilated cavity is provided.

Typical screen materials such as brick veneer, vinyl siding, precast concrete, wood, natural stone, metal siding, polymer modified stuccos etc. have relatively high vapour resistances, (for brick veneers, between about 25 and 200 ng/s·Pa·m^2). High vapour resistance claddings can greatly retard drying of the inner wythe by evaporation and diffusion. Ventilation drying is therefore a potentially important drying mechanism because it is able to remove the moisture that remains behind claddings with a high water vapour resistance.

Storage

It has become generally accepted that most building construction will not be perfect, and thus wetting will occur. Therefore, more attention is being paid to design approaches that also consider the envelope's drying ability. However, moisture removal occurs at different times than wetting, and thus moisture storage must be provided to bridge the gap in time.

The ability of a wall assembly to store moisture may therefore be an important measure of its durability because storage acts as the vital buffer, or capacitor, between the deposition and removal of moisture. However, if the volume of stored water exceeds the safe level for a material and is present for long enough, deterioration can occur, i.e. rot of wood, freeze-thaw damage of masonry, and corrosion of metal. Therefore, the two most important characteristics of moisture storage are 1. how *much* moisture can be stored and 2. for what *duration* without crossing a performance threshold.

The volume of water that is stored in an envelope can be large, in the order of a few to tens of kg per square meter. This moisture can be stored as vapour, liquid, or solid in a variety of ways:

1. trapped in small depressions or poorly drained portions of assemblies,
2. adhered by surface tension as droplets (or frost, even ice) to materials and surfaces
3. adsorbed in or on hygroscopic building materials (brick, wood, fibrous insulation, paper),
4. retained by capillarity (absorbed) in porous materials
5. in the air as vapour.

Sorption of water vapour by hygroscopic materials is an important storage mechanism. A significant amount of moisture can be stored within a porous material as water vapour molecules adsorb to the large internal surface areas of materials such as wood, concrete and masonry. When a porous material has adsorbed all the moisture it can, further moisture will be stored in the pores and cracks within the material by capillary suction, or by *absorption*. Only when all pores are filled with water is a material saturated. For example, wood will adsorb moisture up to approximately 30% of its mass in the adsorbed state and fully saturated wood can hold two to four times this amount of water. When all easily filled pores of a material are filled with water, the material is capillary saturated. A capillary saturated material will generally not be able to store any more moisture. Water stored in pores generally must leave in vapour form.

Designing Enclosures for Moisture Control

It has been argued above that moisture-related enclosure design must be a balance of wetting, drying, and storage potentials in conjunction with a judicious assessment of the susceptibility and vulnerability of the enclosure materials and sub-assemblies.

The physics of heat, air and moisture flow can be applied with the appropriate material properties, environmental data and assumptions, to predict and understand the wetting, drying and storage potentials. A quantitatively accurate value cannot be calculated for most cases: building enclosure design requires the assessment of relative performance, or pass-fail assessments and the ranking of competing design choices, not absolute values.

Mould Problems on Interior Surfaces

Many mould problems in buildings manifest themselves on interior surfaces. The paper facing of drywall is an excellent mould growth substrate, as are ceiling tiles. The solution to these problems are to maintain the relative humidity of the surface of all interior materials below 80%RH. This requires control of interior sources of liquid water, e.g. rain penetration, plumbing, and spills, as well as interior humidity. It should be noted that liquid wetting of a porous material means that the surface relative humidity will be close to 100% until that material has dried, regardless of the interior humidity levels.

Rain penetration through the enclosure is a not uncommon source of serious mould problems. Sweating cold water pipes, leaky plumbing, and spilled water are other sources of interior moisture that can result in mould. These sources of moisture are usually obvious, but they still require vigilant maintenance and repair, as well as good design to avoid.

Interior humidity is a less well understood phenomenon, and so is addressed in detail below

It has already been pointed out that surface humidities of 80%RH must be avoided if possible – this requires both:

1. the control of interior surface temperatures, and
2. control of the interior relative humidity.

High interior surface temperatures can be achieved through the use of a *uniformly* and well insulated enclosure, which is typical of quality energy-efficient design. Thermal bridging and windwashing are common reasons for low interior surface temperatures. Interior humidity control requires control of moisture production and removal, and this usually is in the form of ventilation with cold dry outside air or dehumidification.

Modern enclosure walls and roofs are sufficiently well insulated that surface condensation in winter should not be a problem. This is so because the interior surface film provides a small proportion of the total thermal resistance and thus the temperature drop across the interior surface film is small. Figure 2 shows how the thermal resistance of the so-called interior air film, acts to decrease the temperature of the surface relative to the interior air. The larger the proportion of the total wall thermal resistance that is provided by the interior air film, the larger the drop in surface temperature.

The effective surface conductance of the surface film, typically assumed to be between 8 and 10 $W/m^2 \cdot {}^oC$ for interior walls, may make up a large portion of the thermal resistance of poorly-insulated assemblies and at thermal bridges. Surface condensation often occurs first in corners and behind furniture because the thermal resistance of the surface film is much higher for these situations (a conductance of about 2 to 4 $W/m^2 \cdot {}^oC$). The lack of convective heat transfer results in lower surface temperature and thus a greater probability of, and severity of, surface condensation.

Cold interior temperatures result in condensation and high surface humidities because of the nature of the water vapour. As the temperature of air drops, the relative humidity increases, until at the dewpoint temperature condensation occurs. The temperature -- relative humidity relationship is described by the pyschrometric chart. A schematic of this relationship is shown in Figure 3. As warm interior air contacts cold surfaces the humidity at increases. Hence, interior air interior with a temperature of 24 C and a relative humidity of 50%RH will result in RH conditions of over 80%RH on surfaces with a temperature of 16 Celsius.

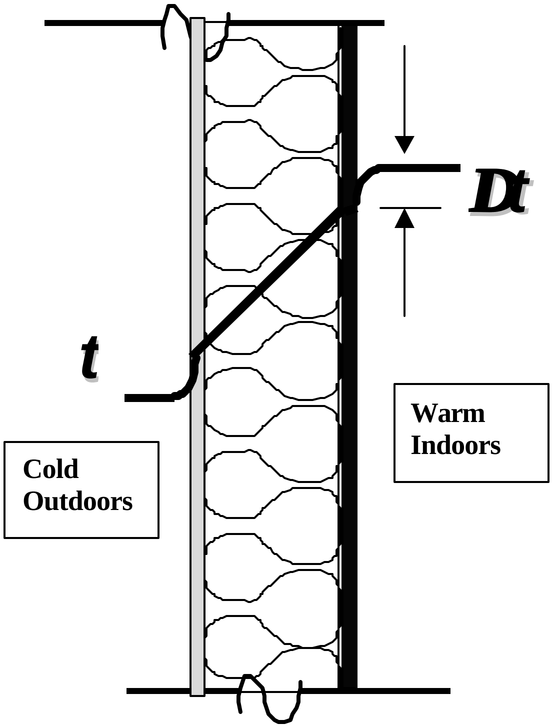


Figure 2: Temperature Drop At Wall Surface

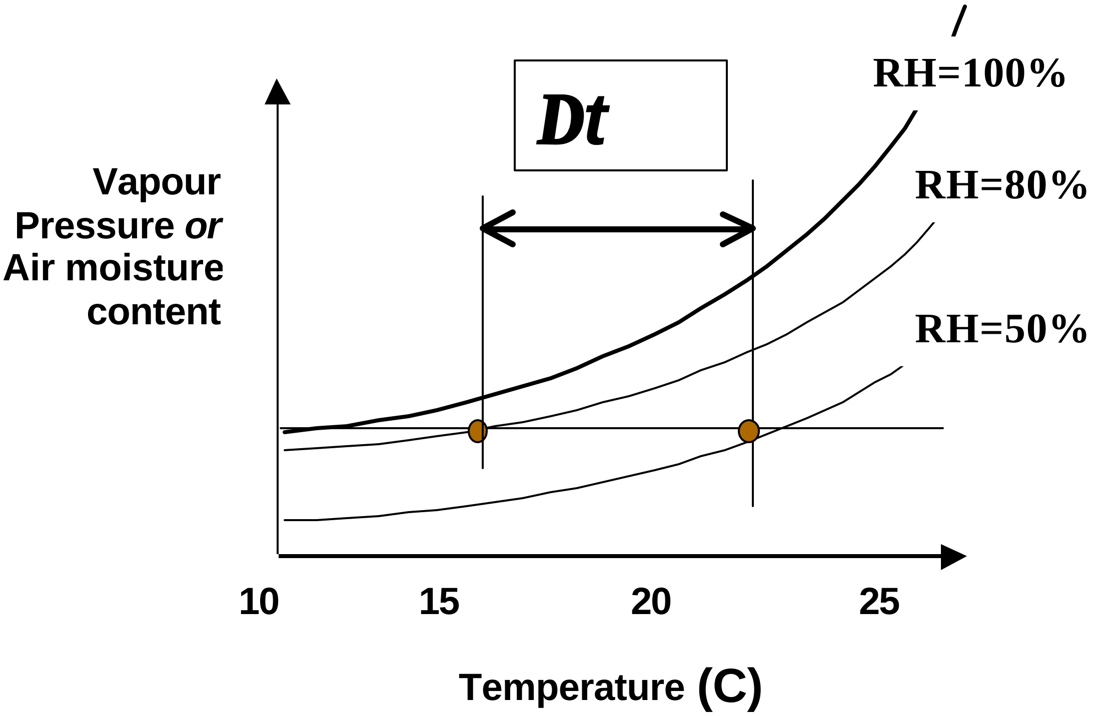


Figure 3: Relative Humidity Change Due to Temperature Drop

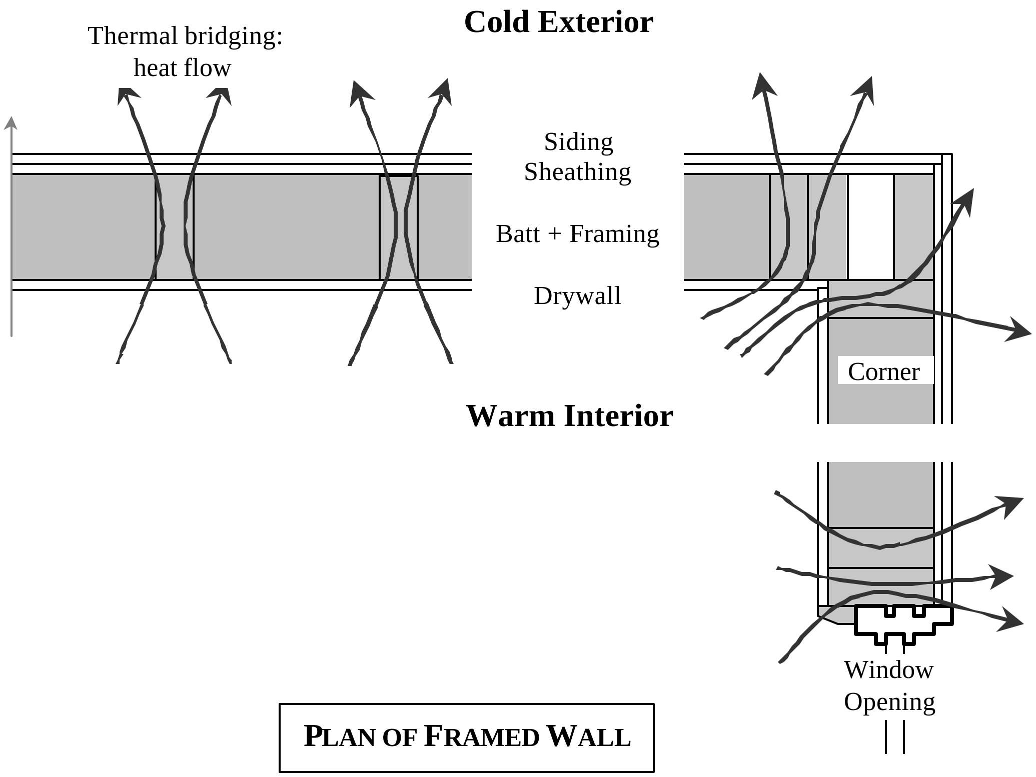
Any situation which results in interior surface temperatures significantly below interior air temperature (i.e., low insulation levels, badly installed insulation, low surface film conductances, wind washing, and thermal bridges) can result in surface condensation and its related problems. Sensitive buildings, e.g., those with high performance standards or high interior humidity, should be thermally analyzed using at least two-dimensional methods, such as computer models.

Thermal bridging, especially by steel framing, or at the intersection of wall corners with roofs and floors, is the one of the most common causes of low surface. Figure 4 provides a schematic of how temperatures at studs and near corners can cause low surface temperatures. In the case of the steel framing shown, an exterior temperature of –10 C can result in interior surface temperatures of 5 to 10 C at studs.

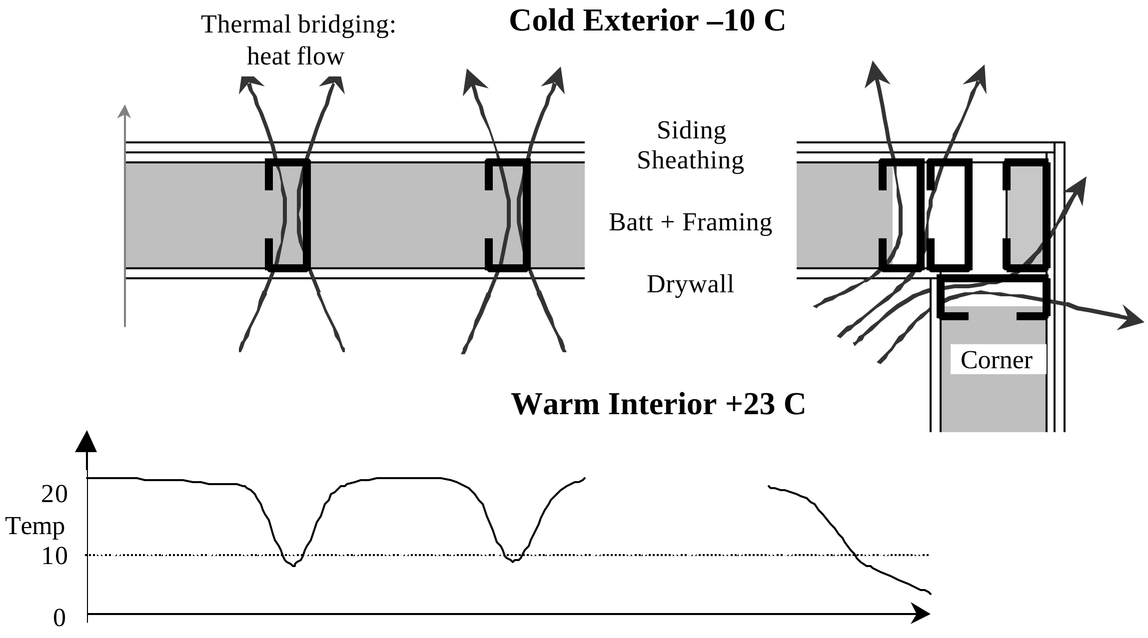
All enclosures should be designed to avoid thermal bridges. The most effective solution, insulating wall sheathings (e.g., rigid foam), are quite useful for "blunting" thermal bridges and also offer energy saving benefits, wind washing resistance, and improved resistance to exfiltration condensation. Convective cooling, or wind-washing, should also be controlled, especially at corners, since this mechanism can result in interior surface temperatures much below those predicted by simple conductive heat transfer (Figure 5).

Windows and doors are often a source of condensation problems in modern buildings because they are not as well insulated as the opaque enclosure. Condensation on window glazing is not directly a problem (other than by reducing visibility) but the moisture may collect, run down and cause staining, mold, and rot. The coldest part of windows with modern double-glazings are typically the lower corners because cold, dense air falls along the surface of the glazing and transports cold air to the bottom of the window. Corners are more susceptible because both the frame and the spacers tend to be more conductive than the glazing unit itself. Very tall and narrow windows (and patio doors) are therefore often the most susceptible to condensation problems.

Because of their low thermal resistance, convective effects (i.e., the effective surface conductance) are more important for windows and doors than walls. Therefore, windows located close to the interior and flush with the interior wall surface will be kept warmer than windows located further out. Curtains and blinds, drawn over windows can dramatically reduce convective transfer and thus cause surface condensation. One method of avoiding condensation on windows is to enhance convective heat transfer by placing a hot-air vent directly below the window. Another more effective and more energy-intensive technique is to heat the window frames with electric heat tracing. Convective heat transfer can be encouraged by forcing pressurized air through a perforated tube that runs around the perimeter of the window frame. Finally, it is often recommended that one open a problem window slightly: this reduces the moisture content of the air in the near vicinity and thereby can reduce condensation problems. Naturally, the use of highly insulated window frames and glazing with insulated spacers should be encouraged, along with the control of interior RH (if possible).



PLAN OF FRAMED WALL



Plot of Temperature Along wall Mid-height

Figure 4: Examples of Thermal Bridging

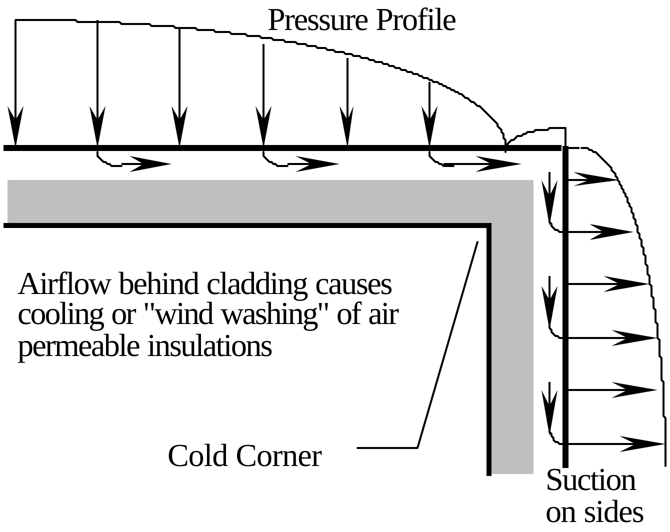


Figure 5: Wind washing and cold corners

Skylights are particularly problematic for a number of reasons. First, night-sky radiation reduces surface temperatures more than for vertical windows. Secondly, skylights are often located in a “tunnel”. This tunnel may be as much as a meter deep and dramatically lowers convective heat transfer. Providing electrical lights in a skylight tunnel acts to replace the light provided by the window at night and the heat given off can maintain the tunnel at a warm temperature. Alternatively, wide and open tunnels will encourage the cold air to fall and be replaced by the warm air near the surface.

In the summer, the interior surfaces of enclosures tend to be warmer than the interior air temperature and condensation is unlikely. However, warm-weather surface condensation on concrete floors can often be a problem in both warm and cold climates. The thermal storage capacity of the concrete causes its temperature to lag behind the air temperature. Also, if the concrete floor is a slab on grade, the cool soil will further reduce the temperature. It is not uncommon for the combined effect of seasonal soil temperature lag and diurnal concrete slab temperature lag to cause as much as a 10 ºC temperature difference between the air and the slab surface. In humid weather these depressed temperatures are likely to cause condensation.

Compounding the problem of massive slabs is the poor convective heat transfer coefficient from the air to the slab (approximately 4 $W/m^2 \cdot {}^oC$ or half that to walls) and the insulating effect of vapour permeable flooring, namely carpet. Carpet covered, uninsulated concrete slab on grade floors are very likely to experience significant surface condensation in humid climates, and the carpet is an ideal mould growing substrate. Concrete slab on grades should be placed on insulation in climates with humid springs and summers. This both reduces the thermal lag and increases the temperature of the concrete. Excessive ventilation should be avoided during humid periods in the spring (when the soil and concrete temperatures are likely to be at a minimum). Carpet should be avoided on all concrete floors installed on grade.

Other surface condensation problems during warm weather tend to be associated with cold water plumbing. Water tanks, such as toilet tanks, and cold water piping within interior partition walls will often attract condensation, especially during warm humid weather. The usual solution is to apply a small amount of insulation, either inside or outside, the tank or pipe.

The moisture content of the interior air depends primarily on two variables:

1. The amount of moisture production within the building
2. The amount of moisture removed by ventilation and/or dehumidification

The effectiveness of ventilation is highly dependent on the moisture content of the outdoor air used for ventilation. In climates with warm winters, such as Vancouver, or humid summers, such as Toronto, the outdoor air contains more moisture and therefore demands higher ventilation rates.

Source	**Strength litres per day**
People - evaporation per person	0.75 (sedate) to 5 (heavy work)
Humidifier	2-20+
Hot tub, Whirlpool	2-20+
Firewood, per cord	1-3
Washing floors etc.	0.2
Dishwashing	0.5
Cooking for four	0.9 to 2 (3 with gas range)
Defrosting (frost free) Fridge	0.5
Typical bathing/washing per person	0.2 to 0.4
Shower (ea)	0.5
Bath (ea)	0.1+
Uncovered Crawlspace / Wet basement	0.5 / m^2
Unvented Gas Appliance	1
Seasonal Desorption (or new materials)	3 - 8 depends on the house construction
Plants/Pets	0.2-0.5 (five plants or one dog)
Total (Typical)	**About 10, but potentially 5 to 40**

Table 1: Moisture Production Estimates (Typ. family of four) (various sources)

A CMHC study found the moisture production rate within detached homes was less than 3 kg/day that less than 10% of the time and less than 21 kg/day for 90% of the time.

Another source of moisture may be the combustion of hydrocarbons. Although most such combustion is directly vented to the exterior, standalone heaters are occasionally use. Natural gas and kerosene produce about 0.15 and 0.10 litres of water per kWh of heat produced respectively.

Figure 6 provides an example of the equilibrium relative humidity for a 108 square meter school portable containing 25 active students. If the ventilation rate (natural plus mechanical) falls below about one air changer per hour (75 liters per second or 160 cubic feet per minute), the humidity levels will increase greatly. As the moisture production rate increases (more students, or from other sources), the humidity level will of course rise. As the outdoor temperature decreases, the interior humidity will fall.

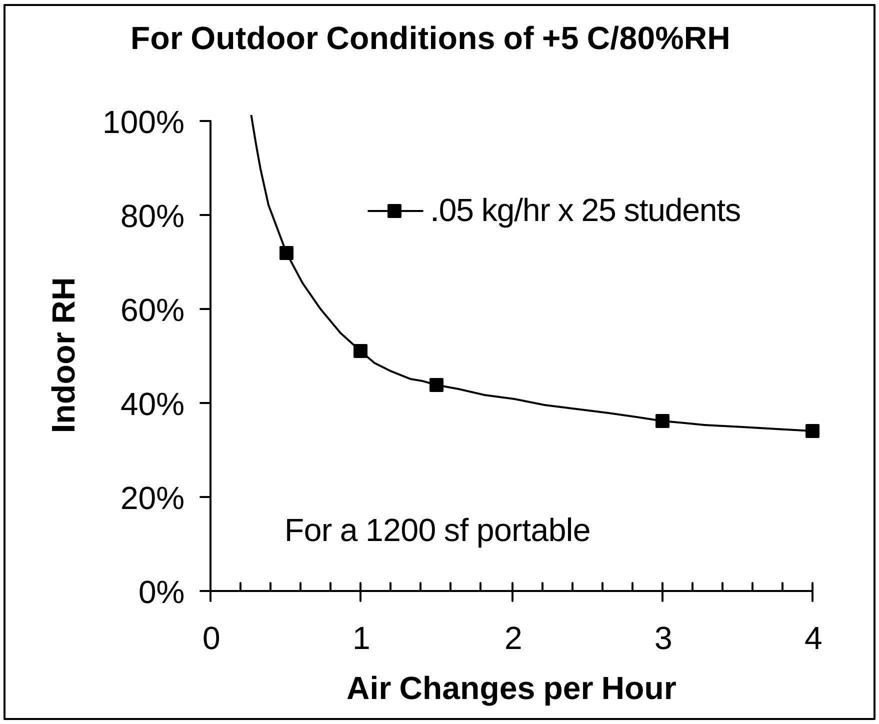


Figure 6: Interior Humidity versus Ventilation Rate

Surface condensation or high surface humidity are often the result of dynamic and short-term temperature or moisture production variations, e.g., a cold and windy night, after a shower or during cooking, during the early morning hours, etc. In schools, for example, a large short-term spike is created when a rush of children enter a classroom, hanging up their wet clothes and stomping off snow from the boots. These short-term and dynamic effects must be considered when conducting a hygrothermal analysis. Some materials are able to adsorb/absorb moisture quickly, e.g., porous lime stuccos, uncoated concrete block, porous brick, cotton etc and thus reduce the potential for surface condensation during short-term events. Materials such as plastic wall coverings and glazed tile floors cannot absorb moisture and will experience surface condensation almost instantaneously after exposure to the proper conditions. The hygric storage capacity of a room can therefore reduce peak interior humidities and even the humidity load out.

Conclusions

Mould is a serious problem for buildings. The most practical means of avoiding mould is to control the amount of moisture available at the surface of materials which support mould growth (and even those that don't, since mould can live on dirt and airborne dust). The control of moisture for mould and other moisture related problems can be achieved by designing for a balance of wetting and drying, supplement by sufficient safe storage capacity to bridge the gap in time.

Sources of liquid water, such as rain penetration, plumbing, and occupant usage must be controlled through good design and timely maintenance.

Maintaining the surface relative humidity below 80%RH is critical to avoiding mould growth, and can be achieved by prov'iding a proper thermal continuous enclosure, good windows, and removing moisture from the interior by ventilation or dehumidification.