

CHAPTER 25

HEAT, AIR, AND MOISTURE CONTROL IN BUILDING ASSEMBLIES—FUNDAMENTALS

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PROPER design of space heating, cooling, and air conditioning requires detailed knowledge of the building envelope’s overall heat, air, and moisture control performance. This chapter provides guidance in the analysis and design of building envelope assemblies for good heat, air, and moisture control performance. Guidance for designing mechanical systems is found in other chapters of the ASHRAE Handbook series. This chapter discusses the fundamentals of combined heat, air, and moisture movement as it relates to envelope assemblies.

Because heat, air, and moisture transfer are coupled and closely interact with each other, they should not be treated separately. In fact, improving a building envelope’s energy performance may cause moisture-related problems. Evaporation of water or removal of moisture by any other means are processes that may require considerable energy that is not always available. Only a sophisticated moisture control strategy can ensure hygienic conditions and adequate durability for modern, energy-efficient building assemblies. Effective moisture control design must deal with all hygrothermal loads (heat and humidity) acting on the building envelope.

TERMINOLOGY AND SYMBOLS

The following heat, air, and moisture definitions and symbols are commonly used.

A **building envelope** or **building enclosure** provides physical separation between the indoor and outdoor environments. A **building assembly** is any part of the building enclosure, such as wall assembly, window assembly, or roof assembly, that has boundary conditions at the interior and the exterior of the building. A **building component** is any element or material within a building assembly.

Heat

Specific heat capacity c is the change in heat (energy) of unit mass of material for unit change of temperature in Btu/lb·°F.

Volumetric heat capacity ρc is the change in heat stored in unit volume of material for unit change of temperature, in Btu/ft³·°F.

The vector **heat flux** q is the time rate of heat transfer through a unit area, in Btu/h·ft².

Thermal conductivity k [also often the Greek letter λ (lambda)] is the steady-state heat flux through a unit thickness of a homogeneous material in a direction perpendicular to the isothermal planes, induced by a unit temperature difference. (ASTM *Standard C168* defines homogeneity.) Units are Btu·in/h·ft²·°F (preferred) or Btu/h·ft·°F. Thermal conductivity must be evaluated for a specific mean temperature, thickness, age, and moisture content. For porous

materials, heat flows by a combination of conduction, convection, radiation, and latent heat exchange and may depend on orientation, direction, or both. The measured property of such materials is called **apparent thermal conductivity**. The specific test conditions (i.e., sample thickness, orientation, environment, environmental pressure, surface temperature, mean temperature, temperature difference, and moisture distribution) should be reported with the values. The symbol k_{app} is used to denote the lack of pure conduction or to indicate that all values reported are apparent. Materials with a low apparent thermal conductivity are called *insulation* materials (see [Chapter 26](#) for more detail).

Thermal resistivity R_u is the reciprocal of thermal conductivity. Units are h·ft²·°F/Btu·in.

Thermal conductance C is the heat flux through a flat body induced by a unit temperature difference between the surfaces of that body. Units are Btu/h·ft²·°F. When the two defined surfaces have unequal areas, as with heat flux through materials of nonuniform thickness, an appropriate mean area and mean thickness must be given. Thermal conductance formulas involving materials that are not uniform slabs must contain shape factors to account for the area variation involved. When heat flux occurs by conduction alone, the thermal conductance of a layer may be obtained by dividing the material’s thermal conductivity by its thickness. When several modes of heat transfer are involved, the **apparent thermal conductance** may be obtained by dividing the material’s apparent thermal conductivity by its thickness. When air circulates within or passes through insulation, as may happen in low-density fibrous materials, the apparent thermal conductance is affected. Thermal conductances and resistances of common building and insulation materials are listed in [Chapter 26](#).

Thermal resistance R is the mean temperature difference between two defined surfaces of material or construction under steady-state conditions that induces a unit heat flux, in ft²·h·°F/Btu.

Heat transfer film coefficient h_i or h_o is heat transferred by convection and radiation between an inside or outside surface and the surrounding environment per unit time and unit area, induced by a unit temperature difference between the surface and reference temperature in the surrounding environment. Units are Btu/h·ft²·°F.

Surface film resistance R_i or R_o is the reciprocal of the inside or outside surface heat transfer film coefficient, in ft²·h·°F/Btu. For convection to occur, the surrounding space must be filled with air or another fluid. If the space is evacuated, heat flow occurs by radiation only.

Thermal transmittance U is the heat flux under steady-state conditions from the environment on the one side of a body to the environment on the other side, per unit temperature difference between the two environments, in Btu/h·ft²·°F. Thermal transmittance is sometimes called the **overall coefficient of heat transfer** or

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U-factor. Thermal transmittance includes surface film conductance.

Thermal emittance ϵ is the ratio of radiant flux emitted by a surface to that emitted by a black surface at the same temperature.

Effective emittance of an air space E is the combined effect of emittances from the boundary surfaces of an air space, where the boundaries are parallel and of a dimension much larger than the distance between them. Chapter 26 lists values of E for various air spaces.

Air

Air transfer M_a is airflow induced by an air pressure difference, caused by wind, stack effect, or mechanical systems, in lb_m/s .

Air flux m_a , a vector, is the time rate of air transfer through a unit area, in $\text{lb}/\text{ft}^2 \cdot \text{h}$.

Air permeability k_a is the air flux through a unit thickness of homogeneous material in a direction perpendicular to the isobaric planes, induced by a unit air pressure difference. Units are in $\text{lb}/\text{ft} \cdot \text{h} \cdot \text{in. Hg}$ or $\text{lb}/\text{ft} \cdot \text{s} \cdot \text{in. Hg}$.

Air permeance K_a is the time rate of air transfer through a unit surface of a porous membrane or layer induced by a unit air pressure difference over that layer. Units are $\text{lb}/\text{ft} \cdot \text{h} \cdot \text{in. Hg}$ or $\text{lb}/\text{h} \cdot \text{in. Hg}$.

Moisture

Moisture content w is the amount of moisture per unit volume of porous material, in lb/ft^3 .

Moisture ratio X (in weight) or Ψ (in volume) is the amount of moisture per unit weight of dry porous material or the volume of moisture per unit volume of dry material, in percent.

Specific moisture content is the ratio between a change in moisture content and the corresponding change in driving potential.

Specific moisture ratio is the ratio between a change in moisture ratio and the corresponding change in driving potential.

Water vapor flux m_v , is the time rate of water vapor transfer through a unit area, in $\text{lb}/\text{ft}^2 \cdot \text{h}$.

Water vapor permeance M is the water vapor flux by diffusion through a unit area of a flat layer, induced by a unit partial water vapor pressure difference across that layer, in $\text{lb}/\text{ft}^2 \cdot \text{h} \cdot \text{in. Hg}$.

Water vapor permeability μ_p is the water vapor flux through a unit thickness of homogeneous material in a direction perpendicular to the isobaric planes, induced by a unit partial water vapor pressure difference, under specified temperature and humidity. Units are $\text{lb}/\text{ft} \cdot \text{h} \cdot \text{in. Hg}$. When permeability varies with psychrometric conditions, the specific permeability defines the property at a specific condition.

Water vapor resistance Z is the reciprocal of water vapor permeance, in $\text{ft}^2 \cdot \text{h} \cdot \text{in. Hg}/\text{kg}$.

Moisture transfer M_m is the moisture flow induced by a difference in suction or in relative humidity, in lb/h .

Moisture flux m_m , a vector, is the time rate of moisture transfer through a unit area, in $\text{lb}/\text{ft}^2 \cdot \text{h}$.

Moisture permeability k_m is the moisture flux through a unit thickness of a homogeneous material in a direction perpendicular to the isosuction planes, induced by a unit difference in suction. Units are $\text{lb}/\text{ft} \cdot \text{h} \cdot \text{in. Hg}$ (suction).

Moisture diffusivity D_m is the ratio between the moisture permeability and the volumetric moisture capacity, in ft^2/h .

ENVIRONMENTAL HYGROTHERMAL LOADS

The main function of the building enclosure is separation of indoor spaces from the outdoor climate. This section describes the hygrothermal loads acting on the building envelope. The purpose of these load descriptions is to predict their influence on the hygrothermal behavior of building assemblies, as a basis for design recommendations and moisture control measures (Künzel and Karagiozis

2004). Load estimations for sizing mechanical systems can be found in Chapters 17 and 18.

In Figure 1, the hygrothermal loads relevant for building envelope design are represented schematically for an external wall. Generally, they show diurnal and seasonal variations at the exterior surface and mainly seasonal variations at the interior surface. During daytime, the exterior wall surface heats by solar radiation, leading to evaporation of moisture from the surface layer. Around sunset, when solar radiation decreases, long-wave (infrared) emission may lead to overcooling (cooling below ambient air temperature) of the façade, and exterior surface condensation may occur. The exterior surface is also exposed to moisture from wind-driven precipitation.

Usually, several load cycles overlap (e.g., summer/winter, day/night, rain/sun). Therefore, a precise analysis of the expected hygrothermal loads should be done before starting to design any building envelope component. However, the magnitude of the loads is not always independent of building geometry and the component's properties. Analysis of the transient hygrothermal loads is generally based on hourly meteorological data. However, the determination of local conditions at the envelope's surface is rather complicated and requires specific experience. In some cases, computer simulations are necessary to assess the microclimate acting on differently oriented or inclined building assemblies.

Ambient Temperature and Humidity

Ambient temperature and humidity with respect to (res.) partial vapor pressure are the boundary conditions always affecting both sides of the building envelope. The climate-dependent exterior conditions may show large diurnal and seasonal variations. Therefore, hourly data are required for most building simulations. ASHRAE provides such meteorological data sets, including temperature and relative humidity, for many locations worldwide (see Chapter 14). These data sets usually represent average meteorological years based on long-term observations at specific locations. However, data of more extreme climate conditions may be important to assess the risks of moisture damage. Therefore, Sanders (1996) proposed using data of the coldest or warmest year in 10 years for hygrothermal analysis instead of data from an average year. However, the temperature at the building site may differ from the meteorological reference data when the site's altitude differs from that of the station recording the data. On average, there is a temperature shift of $\pm 1^\circ\text{F}$ for every ± 350 ft. The microclimate around the building may result

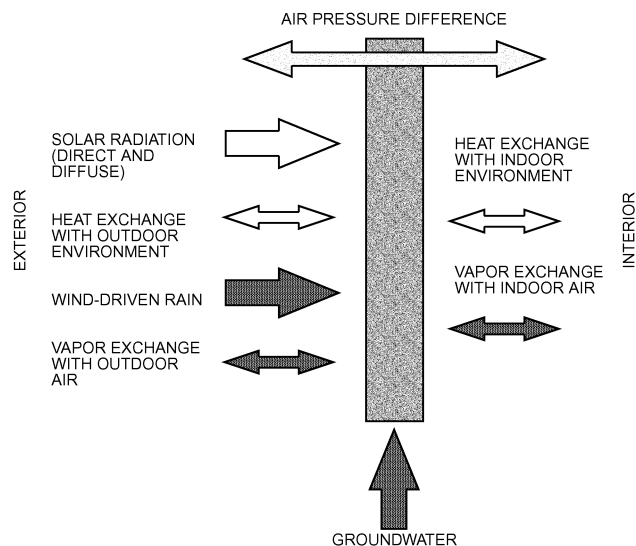


Fig. 1 Hygrothermal Loads and Alternating Diurnal or Seasonal Directions Acting on Building Envelope

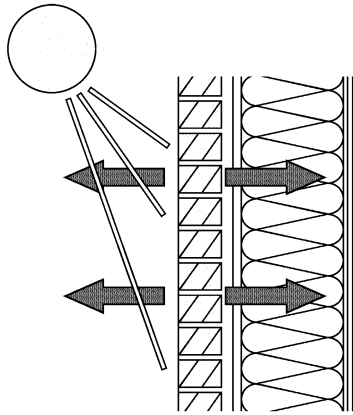


Fig. 2 Solar Vapor Drive and Interstitial Condensation

in an additional temperature shift that depends on the season. For example, the proximity of a lake can moderate seasonal temperature variations, with higher temperatures in winter and lower temperatures in summer compared to sites without water nearby. A low-lying site experiences lower temperatures in winter, whereas city temperatures are higher year round (METEOTEST 2007).

Indoor climate conditions depend on the purpose and occupation of the building. For most commercial constructions, temperature and humidity are controlled by HVAC systems with usually well-defined set points. Indoor conditions in residential buildings are influenced by the outdoor climate and by occupant behavior. The moisture release in an average household is highly variable. According to Sanders (1996), it may range from 6 to 40 lb per day, with an average of approximately 16 lb per day. This moisture must be removed by ventilation or air conditioning. The resulting relative humidity may be determined by hygrothermal whole-building simulation or by simple estimation methods using information on moisture production, air change rates, and climate-dependent HVAC operation (Ten-Wolde and Walker 2001). The presence of spa or swimming pools may increase the load substantially. Information on typical indoor climate conditions of special-purpose constructions like spas, ice rinks, or agricultural buildings and production plants may be found in the 2007 *ASHRAE Handbook—HVAC Applications*.

Solar Radiation

Incident solar radiation is the major thermal load at the building envelope's exterior. For mainly direct solar radiation, the resultant heat source depends on the angle between the sun and the normal of the exposed surface and on its color (short-wave absorptivity). For calculation of incident solar heat flux and spectra, see Chapter 15.

Regarding moisture control, solar radiation is usually considered beneficial unless an envelope component is completely shaded. However, in some cases solar radiation combined with water from precipitation or other sources (e.g., construction moisture) can lead to severe moisture problems. For example, as shown in Figure 2, if the water-absorbing exterior layer of an assembly (e.g., brick veneer, a typical example of “reservoir” cladding) has been wetted by wind-driven rain, heat from solar radiation may drive some of the evaporating water inwards. The resulting high vapor pressure in the cladding causes vapor diffusion toward the ambient air as well as toward the interior of the building assembly, leading to condensation on material layers within the assemblies such as sheathing boards or vapor retarders. Adapting the permeance of vapor retarders and weather-resistive barriers (WRB) to the potential loads may improve the situation. ASHRAE Research Project RP-1091 (Burnett et al. 2004) showed that cladding ventilation is also an effective remedy within specified exterior air humidity limits.

Exterior Condensation

Long-Wave Radiant Effects. Long-wave radiation exchange of the envelope surface with the cold layers of the lower atmosphere is a major heat transfer process. At night or with the sun at a low angle, it results in a net heat flux to the sky (i.e., heat energy sink) (see Chapter 15). Depending on the building assembly's thermal properties, this may lead to a drop in the envelope's surface temperature below the ambient air temperature (overcooling). If the surface temperature reaches the air's dew point, condensation will occur on the exterior surface of the building assembly. Massive structures with a high thermal inertia do not usually lose enough heat to the nighttime radiation sink to bring the surface temperature below the dew point for a significant period of time. However, many modern building assemblies, such as lightweight roofs or exterior insulation finish systems (EIFS), have little thermal inertia in their exterior surface layers and are therefore subject to considerable amounts of exterior condensation (Künzel 2007).

Interior Temperature Differential. Exterior condensation can also occur on poorly insulated assemblies in cooling climates because of the operation of air-conditioning systems. Repeated exterior condensation or long-lasting, high relative humidity often provides the basis for soiling or microbial growth (fungi or algae), which may not be acceptable even though the durability of the assembly is unlikely to be affected.

Effect on Other Layers. Under exterior condensation conditions, ventilated assemblies may also experience condensation within the ventilated air layer. This phenomenon has been discovered by investigating pitched roofs with cathedral ceiling insulation (Hens 1992; Janssens 1998; Künzel and Grosskinski 1989). However, damage cases because of condensation in the ventilation plane are rare, except in metal roofs (Zheng et al. 2004). Occasionally, soiling because of condensate runoff has been reported.

Wind-Driven Rain

The load from rain, especially wind-driven rain, is the main reason for moisture-related building failure. Because the requirements of sometimes costly rain-protection measures depend on the local climate, some countries have introduced regional driving-rain classifications. Generally, coastal regions and those on the windward side of mountains receive the highest precipitation load. Areas of low rainfall do not have the potential for severe wind-driven rain.

Regional precipitation and wind loads are significant factors in determining local wind-driven rain load, but local exposure conditions are of equal importance. A building in the open field receives a higher load than one sheltered by a forest or other buildings. A quantification of exposure conditions for walls depending on landscape, neighborhood, and building size and geometry can be found in the British *Standard* BS 8104 and in the European *ISO/DIN Standard* 15927-3:2006. The average wind-driven rain load R_D in the open ground was investigated by Lacy (1965). It may be estimated from normal rain R_N and the wind velocity component v parallel to the considered orientation, as shown in the following equation:

$$R_D = fvR_N \quad (1)$$

where

R_D = wind-driven rain intensity, lb/ft²·h

f = empirical factor = approximately 0.06 s/ft

v = mean wind velocity, ft/s (or mph)

R_N = rain intensity on a horizontal surface in the open field, lb/ft²·h

Figure 3 shows a typical plot (a “rain rose”) of results from Equation (1) plotted in polar coordinates indicating the amount of wind-driven rain in mass per unit area hitting an unobstructed and isolated vertical surface in the open ground.

The driving rain load close to a façade is considerably less than in the open ground (as shown in Figure 4), and it becomes irregular. Tops and edges of walls generally receive the highest amount of

driving rain deposition. This is caused by the airflow pattern around a building (see Chapter 24 for more information). At the windward side, high pressure gradients coincide with large changes in air velocity. The building acts as an obstacle for the wind, slowing down the airflow and subsequently reducing the wind-driven rain load near the façade. Gravity and the momentum of the rain droplets prevent them from following the airflow around the building, causing them to strike the façade mainly at the edges of the flow obstacle (Straube and Burnett 2000).

However, the irregular driving rain deposition is often evened out by water running off the hard-hit areas, especially when the façade surface has low water absorptivity or the wind-driven rain load is high enough to saturate the most exposed surface layers.

Roof overhangs can reduce the driving rain load on low-rise buildings. Slightly inclined wall sections or protruding façade elements may receive a considerable amount of splash water from façade areas above them, in addition to the direct driving rain deposition. This is often a problem for buildings with walls slightly out of vertical (Hens 2008).

Construction Moisture

Building damage as a result of migrating construction moisture has become more frequent because tight construction schedules leave little time for building materials to dry. Although often disregarded, construction moisture is either delivered with the building products or absorbed by the materials during storage or construction. Cast-in-place concrete, autoclaved aerated concrete (AAC), calcium silicate brick (CSB) and “green” wood are examples of materials that contain significant moisture when delivered. Stucco, mortar, clay brick, and concrete blocks are examples of materials that are either mixed or brought into contact with water at the construction site. All other porous building materials may take up considerable amounts of precipitation or groundwater when left unprotected during storage or construction before the enclosure of the building.

A single-family house made of AAC may initially contain up to 15 tons of water in its walls. Care must be taken to safely remove that water, either by additional ventilation during the first years of

operation or by using construction dryers before putting the building into service. Even “dry” materials have an initial water content of approximately the **equilibrium moisture content at 80% rh (EMC₈₀)**. When significant construction moisture is encountered, EMC₈₀ can be exceeded by a factor of two or more.

Ground- and Surface Water

A high groundwater table or surface water running toward the building and filling the loosefill triangle around the basement represent important moisture loads to the lower parts of the building envelope. These loads should be met by grading the ground away from the building, perimeter drainage, and waterproofing the basement and foundation. Instead of waterproofing by bituminous membranes or coatings, water-impermeable structural elements may be used in building practice (e.g., reinforced concrete, which may, however, be vapor permeable). The resulting vapor flux also presents a load that must be accounted for (e.g., by basement ventilation). Moisture loads in the ground may impair the performance of exterior basement insulation applied on the outside of the waterproofing layer. Therefore, special care must be taken to protect insulation from moisture accumulation unless the insulation material is itself impermeable to water and vapor (e.g., foam glass).

Wicking of ground- or surface water into porous walls by capillary action is called **rising damp**. This phenomenon may be a sign of poor drainage or waterproofing of the building’s basement or foundation. However, other phenomena show moisture patterns similar to rising damp. If the wall is contaminated with salts, which may be the case in historic buildings, there might also be an elevated moisture content in the wall caused by a hygroscopicity increase resulting from water uptake by the salt crystals. Another reason for the appearance of rising damp may actually be surface condensation in unheated buildings during summer.

Air Pressure Differentials

Wind and stack effects caused by differences between indoor and outdoor temperature result in air pressure differentials over the building envelope. In contrast to wind, stack effect is a permanent load that may not be neglected. Worse, stack pressure may act in the same direction as vapor pressure: from inside to outside during the heating season, and in the opposite direction during the cooling season. Therefore, airflow through cracks, imperfect joints, or air-permeable assembly layers may cause interstitial condensation in a manner similar to vapor diffusion. However, condensation caused by stack-induced airflow is likely to be more intense and concentrated around leaks in the building envelope. This can become a problem at the top of a building, which may be especially vulnerable because of leaks at the parapets. To avoid moisture damage, airflow through and within the building envelope should be prevented by a continuous air barrier. Because it is difficult to guarantee total airtightness of the building envelope, the hygrothermal effect of airflow can be quite important, especially when high pressure differentials are expected (e.g., in multistory or mechanically pressurized buildings). For the practical determination of pressure differentials and airflow, see Chapter 16. Air pressures across the envelope may also drive liquid water inward or outward.

HEAT TRANSFER

Heat flow through the building envelope is mainly associated with the energy performance of buildings. However, other aspects of heat transfer are equally important. Interior surface temperature serves not only as an indicator for hygienic conditions in the building (e.g., conditions preventing surface condensation or mold growth), it can also be a major factor for thermal comfort. Temperature peaks and fluctuations within the building envelope or on its surfaces may also affect the envelope’s durability. At low temperature, building materials tend to become less elastic and sometimes brittle, making

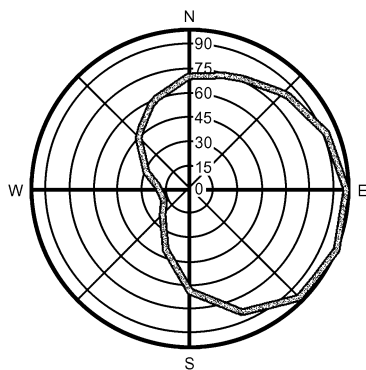


Fig. 3 Typical Wind-Driven Rain Rose for Open Ground

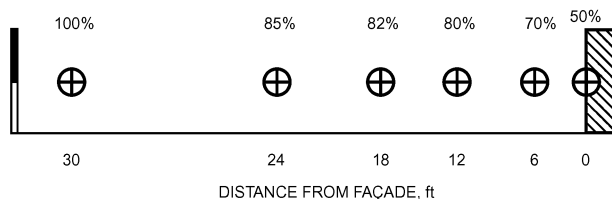


Fig. 4 Measured Reduction in Catch Ratio Close to Façade of One-Story Building at Height of 6 ft

them vulnerable to strain or mechanical impact. At high temperature, some materials degrade because of chemical reactions or irreversible deformation. Deformation and local mechanical failure can also occur under the influence of steep temperature gradients or transients. Whereas some of these aspects can be assessed by steady state calculations (e.g., heating energy losses), others require transient simulations for accurate evaluation.

As explained in Chapter 4, heat transfer by apparent conduction in a solid is governed by Fourier's law:

$$q = -k \text{ grad}(t)$$

$$q = -\left(k_x \frac{dt}{dx} + k_y \frac{dt}{dy} + k_z \frac{dt}{dz}\right) \quad (2)$$

where

q = heat flux, Btu/h · ft²
 t = temperature, °F
 k_x, k_y, k_z = apparent thermal conductivity in direction of $x, y,$ and z axes, Btu/h · ft · °F
 $\text{grad}(t)$ = gradient of temperature (change in temperature per unit length, perpendicular to isothermal surfaces in solid), °F/ft
 dt/dx = gradient of temperature along x axis, °F/ft
 dt/dy = gradient of temperature along y axis, °F/ft
 dt/dz = gradient of temperature along z axis, °F/ft

The thermal conductivity k of the material may be directionally dependent. In fact, many building materials show considerable anisotropy. Examples are wood and wood-based materials, mineral fiber insulation, and perforated bricks. Therefore, $k_x, k_y,$ and k_z are generally not equal.

Substituting Equation (2) into the relationship for conservation of energy yields

$$\frac{\partial h}{\partial t} \times \frac{\partial t}{\partial \tau} = \text{div}[k \text{ grad}(t)] + S$$

$$= \frac{\partial}{\partial x} \left(k_x \frac{\partial t}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial t}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial t}{\partial z} \right) + S \quad (3)$$

where

h = enthalpy per unit volume, Btu/ft³
 S = heat sources and sinks (e.g., caused by latent heat of evaporation/condensation in presence of moisture or chemical reactions such as in concrete hydration), Btu/h · ft³

with

$$\frac{\partial h}{\partial \tau} = \rho_s c_s + w c_w \quad (4)$$

where

ρ_s = density of solid (dry material), lb/ft³
 c_s = specific heat capacity of dry solid, Btu/lb · °F
 c_w = specific heat capacity of liquid water, Btu/lb · °F
 w = moisture content, lb/ft³

STEADY-STATE THERMAL RESPONSE

In steady state without sources or sinks, Equation (3) reduces to

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial t}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial t}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial t}{\partial z} \right) = 0 \quad (5)$$

If the steady-state heat flux is only in one direction (e.g., perpendicular to the building envelope), Equation (2) can be rewritten for each material layer within the building envelope as

$$q = -k_m \frac{\Delta t}{\Delta x} = -C \Delta t = -\frac{1}{R} \Delta t \quad (6)$$

where

Δt = temperature difference between two interfaces of one material layer, °F
 Δx = layer thickness, ft
 k_m = mean thermal conductivity of material layer with thickness Δx , Btu/h · ft² · °F
 C = thermal conductance of layer with thickness Δx , Btu/h · ft² · °F
 R = thermal resistance of layer with thickness Δx , h · ft² · °F/Btu

Under steady-state conditions, the one-dimensional heat flux is the same through all material layers, but their individual thermal conductance or resistance is usually different.

Thermal Resistance of a Flat Assembly

A single layer's thermal resistance to heat flow is given by the ratio of its thickness to its apparent thermal conductivity. Accordingly, the surface-to-surface thermal resistance of a flat building assembly composed of parallel layers (e.g., a ceiling, floor, or wall), or a curved component if the curvature is small, consists of the sum of the resistances (R-values) of all layers in series:

$$R_s = R_1 + R_2 + R_3 + R_4 + \dots + R_n \quad (7)$$

where

R_1, R_2, \dots, R_n = resistances of individual layers, h · ft² · °F/Btu
 R_s = resistance of building assembly surface to surface (system resistance), h · ft² · °F/Btu

For building components with nonuniform or irregular sections, such as hollow clay and concrete blocks, use the R-value of the unit as manufactured. To obtain the overall resistance (air to air), the surface film resistances R_i and R_o must be added to R .

The surface film resistance and its reciprocal, the heat transfer film coefficient, specify the heat transfer to or from a surface by the combined effect of convection and conduction. Although these contributions are affected by surface roughness and temperature difference between the air and surface, the largest influence is that of air movement, turbulence, and velocity close to the surface. Because air movement at the envelope surface depends on wind speed and direction, as well as flow patterns around the building, which are usually unknown, average film coefficients for interior and exterior heat transfer are normally used. Correlations such as that of Schwarz (1971) link the convective film coefficient to wind speed recorded at a height of 30 ft and to orientation of the surface (windward or leeward side). However, because the surface-to-surface thermal resistance of a wall is usually high compared with the surface film resistances, an exact value is of minor importance for most applications.

Heat is also transported between the envelope's surface and the environment by thermal radiation. Because air is rather permeable to long-wave radiation, the radiative heat exchange takes place between the surface and objects in the environment, not the surrounding air. Heat transfer by radiation between two surfaces is controlled by the character of the surfaces (emittance and reflectance), the temperature difference between them, and the angle factor through which they see each other. Indoors, the external wall surface exchanges radiation with partition walls, floor, and ceiling, furniture, and other external walls. In winter, most of the other surfaces have a higher temperature than the external wall surface; therefore, there is a net heat flux to the external wall by radiative exchange. Outdoors, the external wall surface sees the ground, neighboring buildings, and the sky. Without the sun, thermal radiation from the sky is normally low compared to the radiation from the wall. This means the wall is losing energy to the sky. Especially during clear nights, the temperature of the exterior surface of the external wall may drop below the ambient air temperature. In this case, convective and radiative heat transfer at the surface are opposed to each other.

Combined Convective and Radiative Surface Transfer

For simplicity, convective and radiative surface transfer coefficients are often combined, leading to the **apparent transfer coefficient h** :

$$q = h(t_{en} - t_s) \tag{8}$$

with

$$h = h_c + h_r \tag{9}$$

where

- q = total surface heat transfer, Btu/h·ft²
- h = apparent surface transfer coefficient, Btu/h·ft²·°F
- h_r = surface transfer coefficient to account for long-wave radiation exchange, Btu/h·ft²·°F
- h_c = convective surface transfer coefficient (also called surface film coefficient), Btu/h·ft²·°F
- t_{en} = environmental temperature, °F
- t_s = surface temperature, °F

For indoor surface heat transfer, this approach is acceptable when only the heat transport through the building envelope is considered. Environmental temperature t_{en} includes the temperature of surfaces within the field of view of the considered envelope assembly. When all these surfaces are of partition walls and floors that have the same temperature as the indoor air, t_{en} may be replaced by the indoor air temperature.

This approach becomes questionable when heat transfer at the outdoor surface is concerned. Because radiation to the sky can lead to surface temperatures below ambient air temperature, Equation (8) underestimates the real heat flux when environmental temperature is replaced by outdoor air temperature. Therefore, t_{en} must include all short- and long-wave radiation contributions perpendicular to the assembly's exterior surface. However, t_{en} cannot be used for moisture transfer calculations. Therefore, a more convenient way may be to treat the heat transfer by convection and the radiation exchange separately. In this case, h_r in Equation (9) becomes zero and t_{en} is equal to the outdoor air temperature. The heat exchange by radiation is then calculated by balancing the solar and environmental radiation onto the assembly's exterior surface with the long-wave emission from it.

Steady-state calculation of thermal transport through the building envelope is generally done using surface resistances based on combined surface transfer coefficients, with R being the inverse of h . Because of greater air movement outdoors, the mean thermal resistance at the exterior surface is lower than at the interior surface. Typical ranges for the apparent exterior and interior surface transfer coefficient with surface infrared reflectance ≤ 0.1 (nonmetallic) are

$$R_o = 0.17 \text{ to } 0.34 \text{ h}\cdot\text{ft}^2\cdot\text{°F}/\text{Btu}$$

$$R_i = 0.68 \text{ to } 1.13 \text{ h}\cdot\text{ft}^2\cdot\text{°F}/\text{Btu}$$

To calculate thermal transmittance U , the lower values of R should be used. To calculate interior surface film temperature for risk assessment of surface condensation or mold growth, the higher interior and lower exterior R values should be used.

Heat Flow Across an Air Space

Heat flow across an air space is affected by the nature of the boundary surfaces, orientation of the air space, distance between boundary surfaces, and direction of heat flow. Air space thermal conductance, the reciprocal of the air space thermal resistance, is the sum of a radiation component, a conduction component, and a convection component. For computational purposes, spaces are considered airtight, with neither air leakage nor air washing along the boundary surfaces.

The radiation portion is affected by the temperature of the two boundary surfaces and by their respective surface properties. For surfaces that can be considered ideal gray, the surface properties are emittance, absorptance, and reflectance. Chapter 4 explains all three in depth. For an opaque surface, reflectance is equal to one minus the emittance, which varies with surface type and condition and radiation wavelength. The combined effect of the emittances of the two boundary surfaces is expressed by the effective emittance E of the air space. Table 2 in Chapter 26 lists typical emittance values for reflective surfaces and building materials, and the corresponding effective emittance for air spaces. More exact surface emittance values should be obtained by tests. The radiation component is not affected by the thickness of the air space, its orientation, direction of heat flow, or order of emittance (i.e., which surface is hot or cold).

In contrast, heat transfer by convection is affected markedly by the orientation of the air space, direction of heat flow, temperature difference across the space, and, in some cases, thickness of the space. It is also slightly affected by the mean temperatures of both surfaces. For air spaces in building components, radiation and convection components both contribute to the total heat flow. An example of the magnitudes of heat flow by radiation and convection/ conduction across a vertical or horizontal airspace (up and down) is given in Figure 5.

Table 3 in Chapter 26 lists typical thermal resistance values of sealed air spaces of uniform thickness with moderately smooth, plane, parallel surfaces. These data are based on experimental measurements (Robinson et al. 1954). Resistance values for systems with air spaces can be estimated from these results if emittance values are corrected for field conditions. However, for some common composite building insulation systems involving mass-type insulation with a reflective surface in conjunction with an air space, the resistance value may be appreciably lower than the estimated value, particularly if the air space is not sealed or of uniform thickness (Palfey 1980). For critical applications, a particular design's effectiveness should be confirmed by actual test data undertaken by using the ASTM hot-box method (ASTM Standard C1363). This test is especially necessary for constructions combining reflective and non-reflective thermal insulation.

Total Thermal Resistance of a Flat Building Assembly

Total thermal resistance to heat flow through a flat building component composed of parallel layers between the environments at both sides is given by

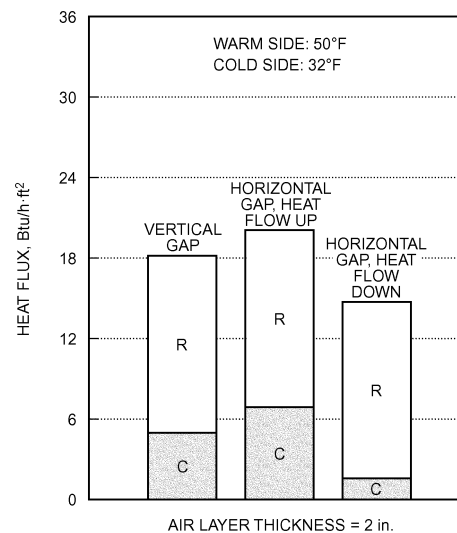


Fig. 5 Heat Flux by Thermal Radiation and Combined Convection and Conduction Across Vertical or Horizontal Air Layer

$$R_T = R_i + R_s + R_o \quad (10)$$

where

R_i = apparent thermal resistance of interior surface film, $\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}/\text{Btu}$

R_o = apparent thermal resistance of exterior surface film, $\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}/\text{Btu}$

R_s = resistance of building assembly surface to surface (system resistance), $\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}/\text{Btu}$

Thermal Transmittance of a Flat Building Assembly

The thermal transmittance or U-factor of a flat building assembly is the reciprocal of R_T :

$$U = 1/R_T \quad (11)$$

Calculating thermal transmittance requires knowing the (1) apparent thermal resistance of all homogeneous layers, (2) thermal resistance of the nonhomogeneous layers, (3) surface film resistances at both sides of the construction, and (4) thermal resistances of air spaces in the construction. The steady-state heat flux Q_n across the building envelope assembly is then defined by

$$Q_n = A_n U_n (t_i - t_o) \quad (12)$$

where

t_i, t_o = indoor and outdoor reference temperatures, $^\circ\text{F}$

A_n = component area, ft^2

U_n = U-factor of component, $\text{Btu}/\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}$

Interface Temperatures in a Flat Building Component

The temperature drop through any layer of an assembly is proportional to its resistance. Thus, the temperature drop Δt_j through R_j is

$$\Delta t_j = \frac{R_j(t_i - t_o)}{R_T} \quad (13)$$

The temperature in an interface j then becomes ($t_o < t_i$)

$$t_j = t_o + \frac{R_o^j}{R_T}(t_i - t_o) \quad (14)$$

where R_o^j is the sum of thermal resistances between inside and interface j in flat assembly, in $\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F}/\text{Btu}$.

If the apparent thermal conductivity of materials in a building component is highly temperature-dependent, the mean temperature must be known before assigning an appropriate thermal resistance. In such a case, use trial and error: first, select the R-values for the particular layers. Then calculate total resistance R_T with Equation (10) and the temperature at each interface using Equation (14). The mean temperature in each layer (arithmetic mean of its surface temperatures) can then be used to obtain second-generation R-values. The procedure is repeated until the R-values are correctly selected for the resulting mean temperatures. Generally, this is done in two or three trial calculations.

Series and Parallel Heat Flow Paths

In many building assemblies (e.g., wood-frame construction), components are arranged so that heat flows in parallel paths of different conductances. If no heat flows through lateral paths, the thermal transmittance through each path may be calculated. The average transmittance of the enclosure is then

$$U_{av} = aU_a + bU_b + \dots + nU_n \quad (15)$$

where a, b, \dots, n are the surface-weighted path fractions for a typical basic area composed of several different paths with transmittances U_a, U_b, \dots, U_n .

If heat can flow laterally with little resistance in any continuous layer, so that transverse isothermal planes result, the flat construction performs as a series combination of layers, of which one or more provide parallel paths. Total average resistance $R_{T(av)}$ in that case is the sum of the resistance of the layers between the isothermal planes, each layer being calculated and the results weighted by contributing surface area. For further information, see Chapter 27.

The U-factor, assuming parallel heat flow only, is usually lower than that assuming combined series-parallel heat flow. The actual U-factor lies between the two. Without test results, a best choice must be selected. Generally, if the construction contains a layer in which lateral conduction is somewhat high compared to heat flux through the wall, a value closer to the series-parallel calculation should be used. If, however, there is no layer of high lateral conductance, use a value closer to the parallel calculation. For assemblies with large differences in material conductivities (e.g., assemblies using metal structural elements), the zone method is recommended (see Chapter 27). An alternative is using linear and punctual thermal transmittances. These characterize the excess heat transfer per degree temperature difference caused by a linear or local thermal bridge.

Thermal Bridges and Whole-Assembly Thermal Transmittance

In many envelope constructions, heat flow develops two- or three-dimensionally (**thermal bridging**). Heat loss and gain through thermal bridges are higher than their share in total surface may suggest. In heating climates, the inside surface may also be colder than the surrounding surfaces. This makes thermal bridges likely places for dirt deposit and mold growth because of elevated moisture content of surfaces in equilibrium with higher relative humidity.

The hot-box method (ASTM Standard C1363) or a multidimensional computer model should be used to determine the overall thermal transmittance of a wall with thermal bridges. Computer models also give the temperatures and heat fluxes.

For flat-wall thermal bridging calculations, refer to the zone and modified zone methods described in Chapter 27. Two- and three-dimensional thermal bridging estimates require the use of appropriate computer modeling tools.

TRANSIENT THERMAL RESPONSE

Steady-state calculations are used to define the average heating energy demand in cold climates. However, in climates where daily temperature swings oscillate around a comfortable mean temperature, transient analysis is more appropriate. The thermal response of a building to daily swings in temperature and solar radiation depends on the properties of its opaque and transparent (fenestration) envelope components and on its operation. The effects on the mutual dependences of the different factors are rather complex and there is no simplified approach that can account for these interactions. Therefore, whole-building simulations complying with ANSI/ASHRAE Standard 140 are recommended.

AIRFLOW

Air transfer in and through building components develops when the air permeance of the component differs from zero. Driving forces are stack pressure, wind pressure, and pressure differences induced by the mechanical system; see Chapters 16 and 24 for more details. When performing air flux calculations through a building component, distinguish between open porous materials and the openings

that occur with layers, cavities, cracks, leaks, and intentionally installed vents. Air flux through an open porous material is given by

$$m_a = -k_a \text{grad}(P_a) \quad (16)$$

where

m_a = air flux, lb/(ft²·h)
 k_a = air permeability of open porous material, lb/ft·h·in. Hg
 $\text{grad}(P_a)$ = gradient in total air pressure (stack, wind, and mechanical systems), in. Hg/ft

For openings in layers, cavities, cracks, leaks, and intentionally installed vents, the air flux (fractionated layers) or air transfer equation (all other) is

$$m_a \text{ or } M_a = C(\Delta P_a)^n \quad (17)$$

where the flow coefficient C and flow exponent n are determined experimentally.

A single layer with low air permeability (an **airflow retarder**) minimizes air flux through an assembly. The main function of an airflow retarder is to minimize airflow through an assembly, so the retarder must be continuous and leak-free. It must also be strong enough to withstand the air pressure difference.

When a building component contains coupled discrete layers, cavities, cracks, leaks, and intentionally installed vents, airflow becomes three-dimensional. For such cases, Kronvall (1982) developed an equivalent hydraulic network methodology, which was adapted by Janssens (1998) to calculate airflow in lightweight sloped roofs.

Water Vapor Flow by Air Movement

Air not only transports heat but also the water vapor the air contains. The water vapor flux is represented by

$$m_v = W m_a \approx \frac{0.62}{P_a} m_a p \quad (18)$$

where

W = humidity ratio of moving air
 m_a = air flux, lb/ft²·h
 p = partial water vapor pressure in air, in. Hg
 P_a = atmospheric air pressure, in. Hg

Even small air fluxes can carry large amounts of water vapor when compared to vapor diffusion. However, potentially damaging airflow always takes place through cracks and leaky joints rather than through the entire area of a building component.

Heat Flux with Airflow

Air leakage through building components may increase ventilation in a building beyond that needed for comfort and indoor air quality (see [Chapter 16](#)). Air also carries heat that may degrade a building's thermal performance. Airflow changes the assumption at the basis of Equation (2) that no mass flow develops in the solid. The sensible heat flux q that moves together with the air is

$$q = c_a m_a t \quad (19)$$

where q is in Btu/h·ft² and c_a is the specific heat capacity of air, Btu/lb·°F.

MOISTURE TRANSFER

Moisture may enter a building envelope by various paths, including built-in moisture, water leaks, wind-driven rain, and foundation leaks. Water vapor activates sorption in the envelope materials, and water vapor flow in and through the envelope may cause condensation on both nonporous and wet, porous surfaces.

Visible and invisible degradation caused by moisture is an important factor limiting the useful life of a building. Invisible degradation includes the decrease of thermal resistance of building and insulating materials and the decrease in strength and stiffness of load-bearing materials. Visible degradation includes (1) mold on surfaces, (2) decay of wood-based materials, (3) spalling of masonry and concrete caused by freeze/thaw cycles, (4) hydration of plastic materials, (5) corrosion of metals, (6) damage from expansion of materials (e.g., buckling of wood floors), and (7) decline in appearance. In addition, high moisture levels can lead to odors and mold spores in indoor air.

MOISTURE STORAGE IN BUILDING MATERIALS

Many building materials are porous. The pores provide a large internal surface, which generally has an affinity for water molecules. In some materials, such as wood, moisture may also be adsorbed in the cell wall itself. The amount of water in these **hygroscopic** (water-attracting) materials is related to the relative humidity of surrounding air. When relative humidity rises, hygroscopic materials gain moisture (**adsorption**), and when relative humidity drops, they lose moisture (**desorption**). The relationship between relative humidity and moisture content at a particular temperature is represented in a graph called the **sorption isotherm** ([Figure 6](#)). Isotherms obtained by adsorption are not identical to isotherms obtained by desorption; this difference is called **hysteresis**. At high relative humidity, small pores become entirely filled with water by capillary condensation. The maximum moisture content should be reached at 100% rh, when all pores are water-filled, but experimentally this can only be achieved in a vacuum, by boiling the material or by keeping it in contact with water for an extremely long time. In practice, the maximum moisture content of a porous material is lower. That value is referred to as **free water saturation** w_f or sometimes **capillary moisture content**. [Figure 6](#) shows a typical sorption curve, giving the equilibrium moisture content as a function of relative humidity. The equilibrium moisture content increases with relative humidity, especially above 80% rh. It decreases slightly with increasing temperature. Moisture contents above w_{05} (the equilibrium water content at 95% rh) cannot be achieved solely by vapor adsorption, because this region is characterized by capillary (unbound) water.

[Chapter 32](#) describes hygroscopic substances and their use as dehumidifying agents. [Chapter 26](#) has data on the moisture content of various materials in equilibrium with the atmosphere at various relative humidity steps. Wood and many other hygroscopic materials change dimensions with variations in moisture content.

Porous materials also absorb liquid water when in contact with it. Liquid water may be present because of leaks, rain penetration, flooding, or surface condensation. Wetting may be so complete that the material reaches free water saturation when the largest pores are filled with water. Up to this point there is still a distinct equilibrium between the moisture content of the material and its environment. This becomes evident when different porous materials are brought in direct (capillary) contact with each other. In that case, there is capillary flow from one material to the other until all pores at a certain size are filled with water in both materials; all pores with sizes above this limit remain empty because smaller capillaries have a higher suction force than larger ones. This phenomenon is used to determine the moisture storage function above 95% rh, which represents the limit of vapor sorption tests in climatic chambers. Dalehaug et al. (2005), Krus (1996), and Roels et al. (2003) described using a pressure plate apparatus, in which water-saturated material samples are placed on a porous membrane permeable to water but impermeable to air. Then pressure is applied in different steps each time until capillary equilibrium is achieved. The equilibrium moisture content at each pressure step is determined by weighing the samples. The moisture storage function from zero pressure (free

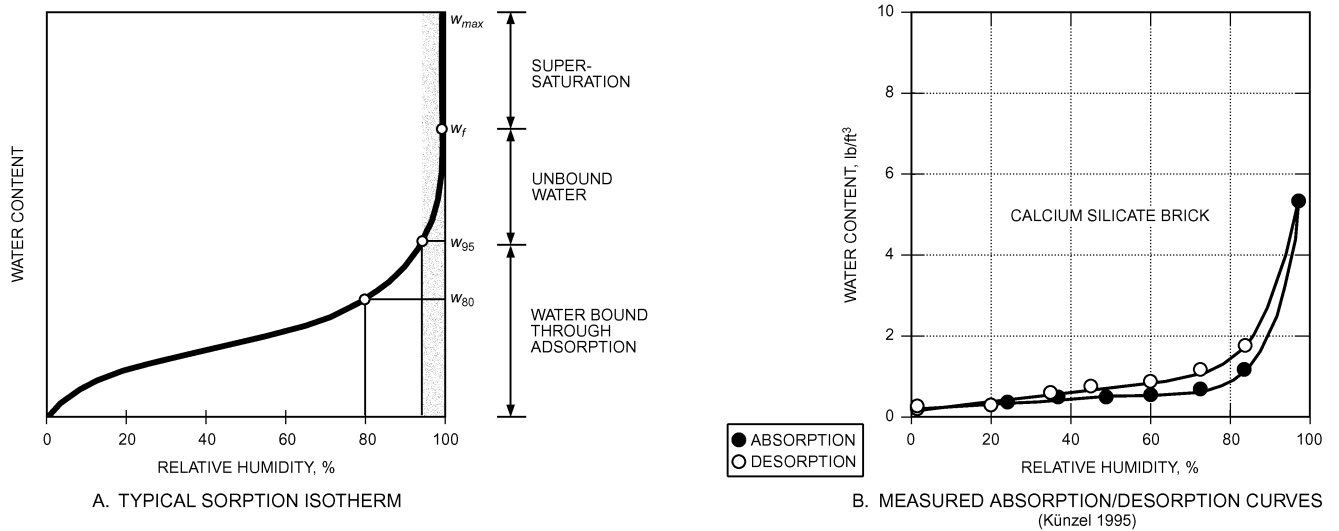


Fig. 6 Sorption Isotherms for Porous Building Materials

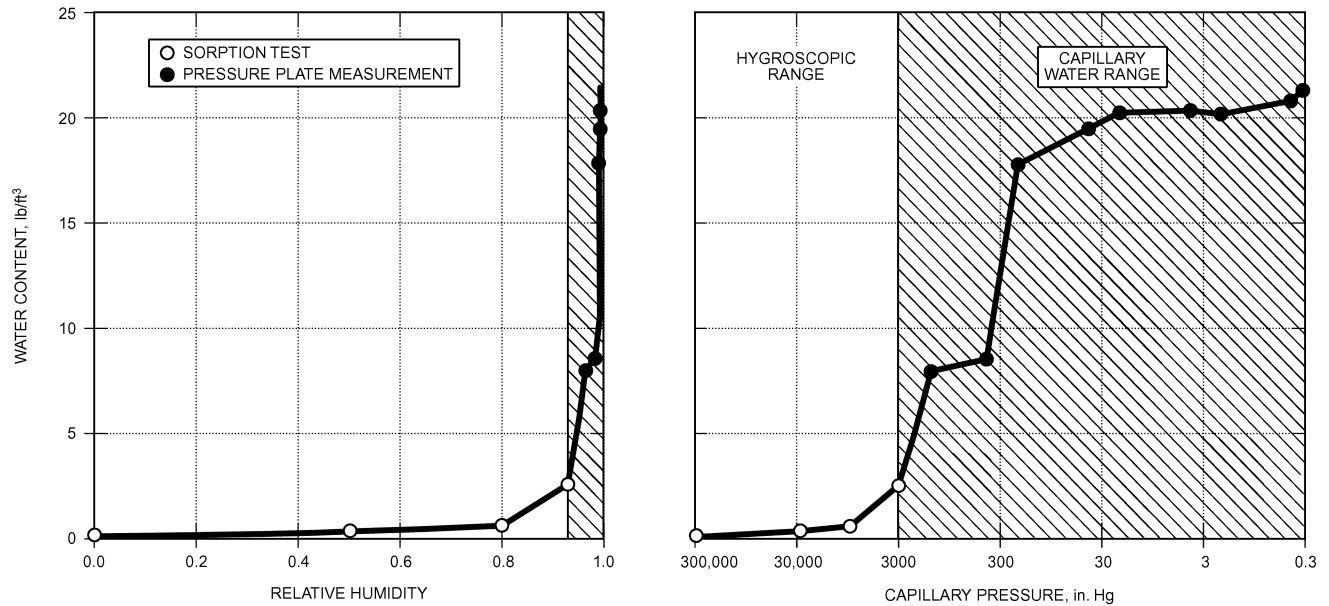


Fig. 7 Sorption Isotherm and Suction Curve for Autoclaved Aerated Concrete (AAC) (Künzel and Holm 2001)

water saturation at 100% rh) up to 2967 in. Hg, which corresponds to approximately 93% rh, is defined by plotting the equilibrium water content over the applied pressure (Figure 7), which is assumed to be equal to the suction pressure of the largest still-water-filled capillaries.

For a continuous moisture storage function from the dry state to 100% rh, the sorption isotherm and the resultant curve from the pressure plate test are combined, either by converting the suction pressure into relative humidity or vice versa, using Kelvin’s equation:

$$\phi = \exp\left(-\frac{s}{\rho_w R_D T}\right) \quad (20)$$

where

ϕ = relative humidity of air in pores

- s = suction pressure, in. Hg
- ρ_w = density of water, lb/ft³
- R_D = gas constant for water vapor, Btu/lb·°R
- T = absolute temperature, °R

The hatched zones in Figure 7 represent the overhygroscopic range where the converted results from the pressure plate tests are plotted to complete the sorption isotherm. This narrow range is less important if vapor diffusion is the dominant moisture transport mechanism, for which an approximative interpolation of the moisture storage function between the end of the sorption isotherm and the free water saturation suffices. However, if capillary water flow from one material to the other becomes dominant (e.g., water absorption by bricks from mortar or stucco), the influence of the pressure plate results on the outcome of the calculation may not be negligible (Krus 1996). In that case, the detailed suction curve (Figure 7, right) should be used for simulations.

MOISTURE FLOW MECHANISMS

Water vapor and liquid water migrate by a variety of transport mechanisms, including the following:

- Water vapor diffusion by partial water vapor pressure gradients
- Displacement of water vapor by air movement (see the section on Airflow)
- Surface diffusion and capillary suction of liquid water in porous building materials
- Liquid flow by gravity or water and air pressure gradients

In the past, moisture control strategies focused on water vapor diffusion. Displacement of water vapor by air movement was treated superficially, and liquid water transport provoked by wind-driven rain or soil moisture was overlooked almost completely. When present, however, these mechanisms can move far greater amounts of moisture than diffusion does. Therefore, air movement and liquid flow should have a higher priority in moisture control.

Liquid flow by gravity and by pressure gradients is not discussed here, but a short description of the other mechanisms follows. More comprehensive treatment of moisture transport and storage may be found in Hens (1996), Künzle (1995), and Pedersen (1990). For a discussion of water vapor in air, see Chapter 1.

Water Vapor Flow by Diffusion

Water vapor migrates by diffusion through air and building materials, normally in small quantities. Diffusion can be important in industrial applications, such as cold-storage facilities and built-in refrigerators, or in buildings where a high inside partial water vapor pressure is needed. Diffusion control also becomes more important with increasingly airtight construction.

The equation used to calculate water vapor flux by diffusion through materials is based on Fick's law for diffusion of a very dilute gas (water vapor) in a binary system (water vapor and dry air):

$$m_v = -\mu_p \text{grad}(p) \quad (21)$$

where

$\text{grad}(p)$ = gradient of partial water vapor pressure, in. Hg

μ_p = water vapor permeability of porous material, $\text{gr}/\text{ft} \cdot \text{h} \cdot \text{in. Hg}$

According to Equation (21), water vapor flux by diffusion closely parallels Fourier's equation for heat flux by conduction. However, actual diffusion of water vapor through a material is far more complex than the equation suggests. For hygroscopic materials, water vapor permeability may be a function of relative humidity. Also temperature has an impact. The permeability may even vary spatially or by orientation because of variations or anisotropy in the material's porous system.

Test methods for measuring water vapor permeability are described in ASTM Standard E96. Water vapor flux through a material is determined gravimetrically while maintaining constant temperature and partial water vapor pressure differential across the specimen. Tests are usually done in a climatic chamber at controlled temperature (68 or 73°F) and 50% rh. The material samples are sealed to the top of a cup that contains either a desiccant (dry-cup) or water res. salt solution (wet-cup).

Permeability is usually expressed in $\text{grains}/\text{h} \cdot \text{ft} \cdot \text{in. Hg}$ and permeance in $\text{grains}/\text{h} \cdot \text{ft} \cdot \text{in. Hg}$. Whereas *permeability* refers to the water vapor flux per unit thickness, *permeance* is used in reference to a material of a specific thickness. For example, a material that is 2 in. thick generally is assumed to have half the permeance of a 1 in. thick material, even though permeances of many materials often are not strictly proportional to thickness. In many cases, the property ignores the effect of cracks or holes in the surface. It is inappropriate to refer to permeability with regard to inhomogeneous or composite materials, such as structural insulated panels (SIPs) or film-faced insulation batts.

Methods have been developed that allow measurement of water vapor transport with temperature gradients across the specimen (Douglas et al. 1992; Galbraith et al. 1998; Krus 1996). These methods may give more accurate data on water vapor transfer through materials and will eventually allow better distinction between the various transport modes.

There are some plastic materials (e.g., polyamide [Künzel 1999]) where the vapor permeability rises substantially with ambient relative humidity because of slight changes in the pore structure: water molecules squeeze between polymer molecules and thereby create new passages through the material. This effect is called **solution diffusion**. Moisture transport by solution diffusion can be adequately described by Equation (21) using humidity-dependent vapor permeability functions determined by a dry-cup test and wet-cup-tests with several humidity steps.

Water Flow by Capillary Suction

Within small pores of an equivalent diameter less than 0.004 in., molecular attraction between the surface and the water molecules causes capillary suction (Figure 8), defined as

$$s = \frac{2\sigma \cos\theta}{r} \quad (22)$$

where

s = capillary suction, in. Hg

σ = surface tension of water, $\text{lb}_f/\text{in.}$

r = equivalent radius of capillary, in.

θ = contact wetting angle, degrees

The contact wetting angle is the angle between the water meniscus and capillary surface. The smaller this angle, the larger the capillary suction. In hydrophilic (water-attracting) materials, the contact wetting angle is less than 90°; in hydrophobic (water-repelling) materials, it is between 90 and 180°.

Capillary water movement is governed by the gradient in capillary suction s :

$$m_l = -k_m \text{grad}(s) \quad (23)$$

where

m_l = liquid flux, $\text{lb}/\text{ft}^2 \cdot \text{h}$

k_m = water permeability, $\text{lb}/\text{ft} \cdot \text{h} \cdot \text{in. Hg}$

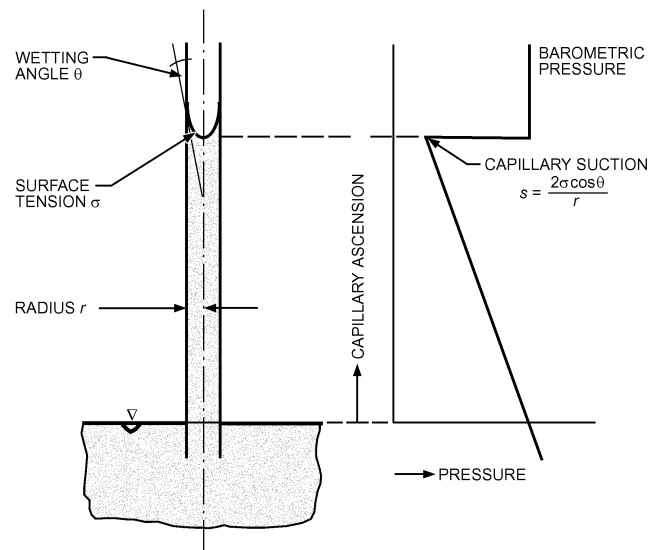


Fig. 8 Capillary Rise in Hydrophilic Materials

Alternatively, replace s with relative humidity [for conversion, see Equation (20)]:

$$m_l = -\delta_\phi \text{ grad}(\phi) \quad (24)$$

where δ_ϕ is the liquid transport coefficient related to the relative humidity as driving potential, in lb/ft³·h.

Capillary suction is greater in smaller capillaries, so water moves from larger to smaller capillaries. In pores with constant equivalent radius, water moves toward zones with smaller contact wetting angles. Although surface tension is a decreasing function of temperature (the higher the temperature, the lower the surface tension) and water moves toward zones with lower temperature, that effect is small compared to the effect of equivalent pore diameter and contact angle.

Capillary suction increases linearly with the inverse of the radius [see Equation (22)], but the flow resistance increases proportionally to the fourth power of the inverse radius. Therefore, larger pores have a much greater liquid transport capacity than smaller pores. Because larger pores can only be filled with water when the smaller pores are already saturated, the liquid transport capacity is a function of moisture content. Thus, water permeability k_m and liquid transport coefficient δ_ϕ are also functions of water content. Determination of these functions is, however, quite difficult because it requires the measurement of suction res. relative humidity distributions during transient water absorption and drying tests (Plagge et al. 2007).

Whereas measuring suction requires experience and special preparation of material samples, determining one-dimensional moisture content distributions in porous building materials can be done accurately with state-of-the-art scanning technologies using nuclear magnetic resonance (NMR), or gamma ray or x-ray attenuation (Krus 1996; Kumaran 1991; van Besien et al. 2002). Transient water content profiles recorded during such scanning tests serve to determine the liquid diffusivity D_w of the examined material, which is defined by

$$m_l = -D_w \text{ grad}(w) \quad (25)$$

where

w = moisture content, lb/ft³

D_w = liquid diffusivity, ft²/h

For most hygroscopic building materials, D_w is a function of moisture content. The diffusivity of calcium silicate brick, a masonry block with hygrothermal behavior that has been investigated extensively, shows an almost exponential increase with water content. As shown in Figure 9, the straight line indicates an exponential increase because the ordinate has a logarithmic scale. This exponential dependence of D_w has been found for many porous materials. Therefore, an exponential approximation is often used when D_w is determined from simple water absorption tests (Kumaran 1999; Künzle 1995).

Although Equation (25), which resembles Fick's law for diffusion, would seem a natural choice for calculating liquid flow, its use is not recommended because water content is not a continuous potential in building envelopes consisting of different materials. Using Equation (23) or (24) is recommended because relative humidity ϕ and capillary suction s are considered to be continuous potentials (no jumps at material interfaces). Where diffusivity functions are available, the liquid transport coefficient δ_ϕ in Equation (24) can be determined by

$$\delta_\phi = D_w \frac{dw}{d\phi} \quad (26)$$

where $dw/d\phi$ is the slope of sorption isotherm res. moisture retention curve, in lb/ft³.

Liquid Flow at Low Moisture Content

The explanation of liquid flow at low moisture content is still a matter of controversy. Some researchers assume it is surface diffusion (e.g., Krus 1996), whereas others believe liquid flow only fully starts beyond critical moisture content (Carmeliet et al. 1999; Kumaran et al. 2003; Vos and Coelman 1967). Liquid flow begins within the hygroscopic range, and is often mistaken for a part of vapor diffusion. In porous materials with a fixed pore structure, the apparent increase in vapor permeability during a wet-cup test may be partly due to liquid transport phenomena, and partly to shorter diffusion paths among water islands in the porous system formed by capillary condensation. Surface diffusion is defined as molecular movement of water adsorbed at the pore walls of the material. The driving potential is the mobility of the molecules, which depends on relative humidity in the pores (i.e., the adsorbed water migrates from zones of high to low relative humidity). Liquid flow, if present at low moisture content, can be described by Equations (23) or (24), as for capillary flow.

Under isothermal conditions, it is impossible to differentiate between vapor and liquid flow at low moisture content. However, in the presence of a temperature gradient, both transport processes may oppose each other in a pore; the fluxes may go in opposite directions (Künzel 1995). This can be explained by looking at the physical processes in a single capillary going through a wall, as shown in Figure 10. In winter, the indoor vapor pressure is usually higher than outdoors while the indoor humidity is lower than outdoor relative humidity. Therefore, the partial vapor pressure gradient is opposed to the relative humidity gradient over the cross section of an exterior wall. Looking at one capillary in that wall under very dry conditions (Figure 10), the only moisture transport mechanism is vapor diffusion and the total flux is directed towards the exterior. If the average humidity in the wall rises to 50 to 80% rh, liquid water begins to move in the opposite direction either by surface diffusion or by capillary suction in the nanopores. Under these conditions, the total moisture flux may go to zero if both fluxes are of the same magnitude (Krus 1996). When conditions are very wet (e.g., from wind-driven rain), most of the capillary pores are filled with water, and the dominant transport mechanism is flow by capillary suction.

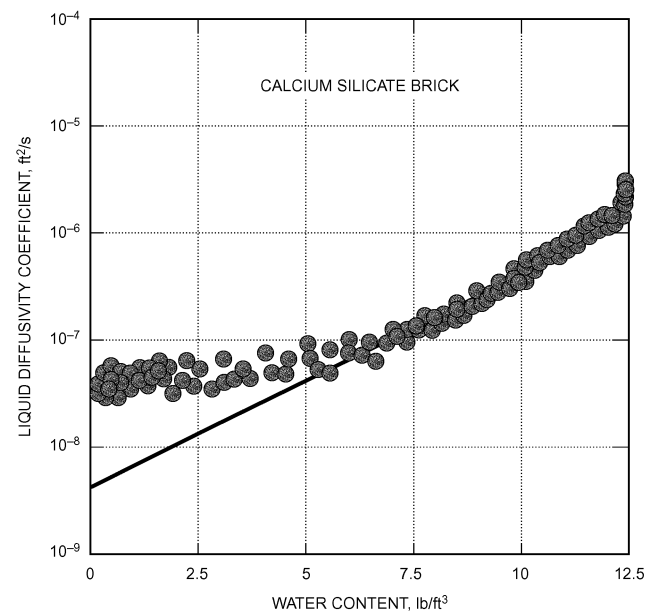


Fig. 9 Moisture-Dependent Diffusivity of Calcium Silicate Brick (CSB) Determined from NMR Scans During Water Absorption Tests (Krus 1996)

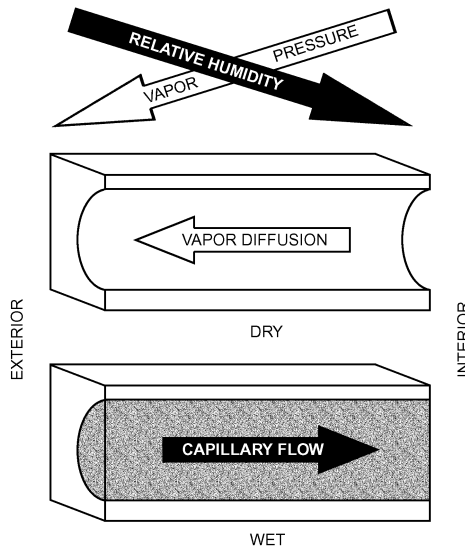


Fig. 10 Moisture Fluxes by Vapor Diffusion and Liquid Flow in Single Capillary of Exterior Wall under Winter Conditions

Transient Moisture Flow

It is difficult to experimentally distinguish between liquid flow by suction and water vapor flow by diffusion in porous, hygroscopic materials. Because these materials have a very complex porous system and each surface is transversed by liquid-filled pore fractions and vapor-filled pore fractions, vapor and liquid flow are often treated as parallel processes. This allows expression of moisture flow as the summation of the two transport equations, one using water vapor pressure to drive water vapor flow by diffusion, and the other using either capillary suction or relative humidity ϕ to drive liquid moisture flow. The conservation equation in that case can be written as

$$\frac{\partial w}{\partial t} = -\text{div}(m_w + m_v) + S_w \quad (27)$$

where

- w = moisture content of building material, lb/ft³
- m_v = water vapor flux, lb/ft²·h
- m_w = liquid water flux, lb/ft²·h
- S_w = moisture source or sink, lb/ft³·h
- div = divergence (resulting inflow or outflow per unit volume of solid), ft⁻¹

Vapor and liquid fluxes are given by Equations (21), (23), and (24), which may be rewritten in terms of only two driving forces, capillary suction pressure s and partial vapor pressure p :

$$\frac{\partial w}{\partial s} \times \frac{\partial s}{\partial t} = \text{div} \left[k_m \text{grad}(s) + \mu_p \text{grad}(p) \right] + S_w \quad (28)$$

where

- s = capillary suction pressure, in. Hg
- p = partial vapor pressure, in. Hg
- μ_p = vapor permeability (related to partial vapor pressure), lb/ft·h·in. Hg
- k_m = water permeability (related to partial suction pressure), lb/ft·h·in. Hg
- S_w = moisture source or sink, lb/ft³·h

Alternatively, suction pressure s in Equation (28) can be replaced by relative humidity as the sole variable, with the saturation pressure p_{sat} only a function of temperature:

$$\frac{\partial w}{\partial \phi} \times \frac{\partial \phi}{\partial t} = \text{div} \left[\delta_\phi \text{grad}(\phi) + \mu_p \text{grad}(\phi p_{sat}) \right] + S_w \quad (29)$$

where

- ϕ = relative humidity, %
- p_{sat} = saturation vapor pressure, in. Hg
- μ_p = vapor permeability (related to partial vapor pressure), lb/ft·h·in. Hg
- δ_ϕ = liquid transport coefficient (related to relative humidity), lb/ft·h

Because of the strong temperature dependence of vapor pressure res. saturation vapor pressure, Equation (28) res. (29) must be coupled with Equation (3) to describe nonisothermal moisture flow. Under isothermal conditions, Equation (28) res. (29) could be solved independently. However, pure isothermal conditions hardly ever exist in reality because as soon as water evaporates or condenses, the latent heat effect leads to temperature differences. Other potentials may be used if material properties appropriate to those potentials are available.

COMBINED HEAT, AIR, AND MOISTURE TRANSFER

The consequences of combined heat, air, and moisture transfer can be detrimental to a building's thermal performance, occupant comfort, and indoor air quality. Air in- and exfiltration short-circuit the U-factor as a designed wall performance. Wind washing, inside air washing, and stack-induced air movement may increment the U-factor by a factor of 2.5 or more. High moisture levels in building materials may also have a negative effect on the thermal performance of the building envelope. Therefore, it is advisable to analyze the combined heat, air, and moisture transfer through building assemblies. However, some of these transport phenomena, especially those involving airflow, are three-dimensional in nature and difficult to predict because they only occur through accidental gaps, cracks, or imperfect joints. Research that attempts to describe these effects is ongoing, but at present, practitioners can only use simplified tools or hygrothermal models that do not yet cover all airflow aspects.

SIMPLIFIED HYGROTHERMAL DESIGN CALCULATIONS AND ANALYSES

SURFACE HUMIDITY AND CONDENSATION

Surface condensation occurs when water vapor contacts a non-porous surface that has a temperature lower than the dew point of the surrounding air. Insulation should therefore be thick enough to ensure that the surface temperature on the warm side of an insulated assembly always exceeds the dew-point temperature there. However, even without reaching the dew point, relative humidity at the surface may become so high that, given enough time, mold growth occurs. According to Hens (1990), a design rule is that surface relative humidity should not exceed 80% on a monthly mean basis.

The temperature ratio f_{h_i} is useful for calculating the surface temperature:

$$f_{h_i} = \frac{t_s - t_o}{t_i - t_o} \quad (30)$$

where

- t_s = surface temperature on warm side, °F
- t_o = ambient temperature on cold side, °F
- t_i = ambient temperature on warm side, °F

The minimum temperature ratio to avoid surface condensation is

$$f_{h_i, min} = \frac{t_{d,i} - t_o}{t_i - t_o} \quad (31)$$

where $t_{d,i}$ is the dew point of ambient air on the warm side, °F.

The minimum insulation thickness to avoid surface condensation on a flat element can be calculated from

$$L_{min} = k \left[\frac{f_{h_i, min}}{h_i(1 - f_{h_i, min})} - R_{add} \right] \quad (32)$$

where R_{add} is the thermal resistance between the surface on the warm side and the cold ambient for the wall without thermal insulation, ft²·h·°F/Btu.

The condensation resistance of glazing is often estimated from outdoor and indoor design temperature, U-factor of the window assembly, and air film resistance. A window assembly may have different U-factors at the glass, frame, and the edge where the glass meets the frame; condensation resistance must be calculated at each of these locations. A procedure for these calculations can be found in NFRC (2004). The likelihood of window condensation depends strongly on the indoor air film resistance. This resistance may be reduced by washing the window with supply air. It may be increased with the use of window treatments such as blinds or curtains. Condensation on glazing is not inherently damaging, unless water is allowed to run onto painted or other surfaces that can be damaged by water.

INTERSTITIAL CONDENSATION AND DRYING

Dew-Point Methods

The best-known simple steady-state design tools for evaluating interstitial condensation and drying within exterior envelopes (walls, roofs, and ceilings) are the dew-point method and the Glaser method (which uses the same underlying principles as the dew-point method, but uses graphic rather than computational methods). These methods assume that steady-state conduction governs heat flow and steady-state diffusion governs water vapor flow. Both analyses compare partial water vapor pressures within the envelope, as calculated by steady-state water vapor diffusion, with saturation water vapor pressures, which are based on calculated steady-state temperatures within the envelope.

The condition where the calculated partial water vapor pressure is greater than saturation has been called **condensation**. Strictly speaking, condensation is the change in phase from vapor to liquid, as occurs on glass, metal, etc. For porous and hygroscopic building materials (e.g., wood, gypsum, masonry materials), vapor may be adsorbed or absorbed and never form the droplets usually associated with true condensation. Nevertheless, the term *condensation* is used for this method to indicate vapor pressure in excess of saturation vapor pressure, although this could be misleading about actual water conditions on porous and hygroscopic surfaces. This is one of the unfortunate simplifications inherent in a steady-state analytic tool.

Steady-state heat conduction and vapor diffusion impose severe limitations on applicability and interpretation. The greatest one is that the main focus is on preventing sustained interstitial condensation, as indicated by vapor pressures beyond saturation vapor pressures. Many building failures (e.g., mold, buckling of siding, paint failure) are not necessarily related to interstitial condensation; conversely, limited interstitial condensation can often be tolerated, depending on the materials involved, temperature conditions, and speed at which the material dries out. (Drying can only be approximated because both the dew-point and Glaser methods neglect moisture storage and capillary flow.) Because all moisture transfer mechanisms except water vapor diffusion are excluded, results should be considered as approximations and should be used with extreme care. Their validity and usefulness depend on judicious selection of boundary conditions, initial conditions, and material

properties. Specifically, the methods should be used to estimate monthly or seasonal mean conditions only, rather than daily or weekly means. Furthermore, water vapor permeances may vary with relative humidity, and rain, flashing imperfections, leaky or poorly formed joints, rain exposure, airflow, and sunshine can have overriding effects. The dew-point and Glaser methods, however, are still used by design professionals and actually form the basis for most codes dealing with moisture control and vapor retarders.

For those who want to use this simple tool despite its shortcomings, a description of the dew-point method is presented in this chapter, with two application examples in Chapter 27. A comprehensive description of the dew-point and Glaser methods can be found in TenWolde (1994).

The dew-point method uses the equations for steady-state heat conduction and diffusion in a flat component, with the vapor flux in a layer written as

$$-m_v = \mu_p \frac{\Delta p}{d} = \frac{\Delta p}{Z} \quad (33)$$

where

- m_v = water vapor flux through layer of material, gr/h·ft²
- Δp = partial water vapor pressure difference across layer, in. Hg
- μ_p = water vapor permeability of material, gr/ft·h·in. Hg
- d = thickness of layer, ft
- Z = water vapor resistance, in. Hg·ft²·h/gr

Over time, upgrades have been added to the dew-point method: (1) the concept of critical moisture content allows accounting for moisture build-up and upgraded calculation of drying, and (2) carried vapor flow has been included, underlining the importance of airtightness to avoid moisture deposition by condensation in building assemblies (Hens 2007; Vos and Coleman 1967).

TRANSIENT COMPUTATIONAL ANALYSIS

Computer models can analyze and predict the heat, air, and moisture response of building components. These transient models can predict the varying hygrothermal situations in building components for different design configurations under various conditions and climates, and their capabilities are continually improved. Hens (1996) reviewed the state of the art of heat, air, and moisture transport modeling for buildings and identified 37 different models, most of which were research tools that are not readily available and may have been too complex for use by practitioners. Some, however, were available either commercially, free of charge, or through a consultant. Also, Trechsel (2001) provides an update on existing tools and approaches.

For many applications and for design guide development, the actual behavior of an assembly under transient climatic conditions must be simulated, to account for short-term processes such as driving rain absorption, summer condensation, and phase changes. Understanding the application limits of a model is an important part of that process.

The features of a complete moisture analysis model include transient heat, air, and moisture transport formulation, incorporating the physics of contact conditions between layers and materials. Interfaces may be bridgeable for vapor diffusion, airflow, and gravity or pressure liquid flow only. They may be ideally capillary (no flow resistance from one layer to the next) or behave as a real contact (have an additional capillary resistance at the interface).

Not all these features are required for every analysis, though additional features may be needed in some applications (e.g., moisture flow through unintentional cracks and intentional openings, rain penetration through veneer walls and exterior cladding). To model these phenomena accurately, experiments may be needed to define subsystem performance under various loads (Straube and

Burnett 1997). It is usually preferable to take performance measurements of system and subsystems in field situations, because only then are all exterior loads and influences captured.

Validation, verification, and benchmarking of combined heat, air, and moisture models is a formidable task. Currently, only limited internationally accepted experimental data exist. The main difficulty lies in the fact that it is difficult to measure air and moisture fluxes and moisture transport potentials, even under laboratory conditions. In addition, even an already validated model should be verified for each new application.

In most full hygrothermal models, common outputs are air pressure; temperature; moisture content; relative humidity; and air, heat, and moisture fluxes. Results must be checked for consistency, accuracy, grid independence, and sensitivity to parameter changes. The results may be used to evaluate the moisture tolerance of an envelope system subjected to various interior and exterior loads. Heat fluxes may be used to determine thermal performance under the influence of moisture and airflow. Furthermore, the transient output data may be used for durability and indoor air quality assessment. Postprocessing tools concerning durability (e.g., corrosion, mold growth, freeze and thaw, hygrothermal stress and strain, indoor air humidity) have been developed or are under development. For instance, Carmeliet (1992) linked full hygrothermal modeling to probability-based fracture mechanics to predict the risk of crack development and growth in an exterior insulation finish system (EIFS) by weathering. A transient model to estimate the rate of mold growth was developed by Sedlbauer (2001).

Transient models have enabled timestep-by-timestep analysis of heat, air, and moisture conditions in building components, and give much more realistic results than steady-state conduction/diffusion and conduction/diffusion/airflow models. However, they are complex and usually not transparent, and require judgment and expertise on the part of the user. Existing models are one- or two-dimensional, requiring the user to devise a realistic representation of a three-dimensional building component. Users should be aware which transport phenomena and types of boundary conditions are included and which are not. For instance, some models are not able to handle air transport or rain wetting of the exterior. The results also tend to be very sensitive to the choice of indoor and outdoor conditions. Usually, exact conditions are not known. Indoor and outdoor conditions to be used have been established by proposed ASHRAE *Standard* 160P. More extensive data on material properties have become available (e.g., Kumaran 2006), but it can be problematic finding accurate data for all the materials in a component. Finally, interpretation of results is not easy: accurate data on the moisture and temperature conditions that materials can tolerate are often not available.

Combined heat, air, and moisture models also have limitations. Rain absorption, for example, can be modeled, but rainwater runoff and its consequences at joints, sills, and parapets cannot, although runoff followed by gravity-induced local penetration is one of the main causes of severe moisture problems. Even an apparently simple problem, such as predicting rain leakage through a brick veneer, is beyond many tools' capabilities. In such cases, simple qualitative schemes and field tests still are the way to proceed.

CRITERIA TO EVALUATE HYGROTHERMAL SIMULATION RESULTS

At the building assembly and whole building level, combined heat, air, and moisture transfer has consequences for thermal comfort, perceived indoor air quality, health, durability, and energy efficiency. The hygrothermal conditions in a building or within a building envelope assembly can be crucial for the overall performance of the construction and its mechanical systems. Therefore, simulation results should be compared to limit conditions and widely accepted performance criteria determined for the following performance issues.

Thermal Comfort

Thermal comfort, defined as a condition of mind that expresses satisfaction with the thermal environment (ASHRAE *Standard* 55), depends on two human parameters (clothing and metabolism) and a set of environmental variables, among them relative humidity. At effective temperatures below 77°F, relative humidity's effect on thermal comfort is minimal, but above 77°F, its importance increases as latent heat loss becomes a main mechanism in getting rid of metabolic heat. If, at those temperatures, the air feels too moist, the thermal environment is perceived as uncomfortable. At low relative humidity, polluted air can irritate the mucosa, and electric discharges when touching insulators (e.g., plastic chairs) are felt. However, in most residential buildings and in many offices, temperature is controlled but not relative humidity, except in hot and humid climates. Its instantaneous value depends on the equilibrium between vapor release indoors, ventilation, airflow among rooms, and temporary vapor storage by finishes and furnishings (often called moisture buffering). The average value over longer periods depends on ventilation and vapor release only, whereas buffering reduces temporary extremes only.

Perceived Air Quality

Air quality may be defined exactly by measuring the pollutants present. However, occupants typically perceive dryer, cooler air as smelling "fresher" than humid, warmer air. Thus, temperature and relative humidity affect perception of air freshness. Together, they define the air's enthalpy. Testing has shown that higher enthalpy lowers the perception of freshness (Fang et al. 1998). Despite this fact, in most buildings, relative humidity is an uncontrolled parameter.

Human Health

Mold in buildings is offensive to occupants. Mold will grow on most surfaces if the relative humidity at the surface is above a critical value, the surface temperature is conducive to growth, and the substrate provides nutritional value to the organism. The growth rate depends on the magnitude and duration of surface relative humidity. Surface relative humidity is a complex function of material moisture content, local surface temperature, and humidity conditions in the space. In recognition of the issue's complexity, the International Energy Agency established a surface relative humidity criterion for design purposes: monthly average values should remain below 80% (Hens 1990). Other proposals include the Canada Mortgage and Housing Corporation's stringent requirement of always keeping surface relative humidity below 65% (CMHC 1999). Although there still is no agreement on which criterion is most appropriate, mold growth can usually be avoided by allowing surface relative humidity over 80% only for short time periods. The relative humidity criterion may be relaxed for nonporous surfaces that are regularly cleaned. Most molds only grow at temperatures above 40°F. Moisture accumulation below 40°F may not cause mold growth if the material is allowed to dry out below the hygroscopic moisture content for a relative humidity of 80% before the temperature rises above 40°F. Mathematical models for predicting a mold growth index were developed by Hukka and Viitanen (1999) and Sedlbauer (2001); these can be linked to results from hygrothermal analysis.

Dust mites trigger allergies and asthma. Dust mites thrive at high relative humidities (over 70%) at room temperature, but will not survive sustained relative humidities below 50% (Burge et al. 1994). Note that these values relate to local conditions in the places that mites tend to inhabit (e.g., mattresses, carpets, soft furniture).

Durability of Finishes and Structure

Moisture behind paint films may cause paint failure, and water or condensation may also cause streaking or staining. Excessive changes in moisture content of wood-based panels or boards may cause buckling or warp. Excessive moisture in masonry and con-

crete may cause salt efflorescence, or, when combined with low temperatures, freeze/thaw damage and spalling (chipping).

Structural failures caused by wood decay are rare but have occurred (Merrill and TenWolde 1989). Decay generally requires wood moisture content at fiber saturation (usually about 30%) or higher and temperatures between 50 and 100°F. Such high wood moisture contents are possible in green lumber or by absorption of liquid water from condensation, leaks, groundwater, or saturated materials in contact with the wood. To maintain a safety margin, 20% moisture content is sometimes used as the maximum allowable moisture level. Because wood moisture content can vary widely with sample location, a local moisture content of 20% or higher may indicate fiber saturation elsewhere. Once established, decay fungi produce water that enables them to maintain moisture conditions conducive to their growth.

Rusting of nails, nail plates, or other metal building components is also a potential cause of structural failure. Corrosion may occur at relative humidities near the metal surface above 60% or as a result of liquid water from elsewhere. Wood moisture content over 20% encourages corrosion of steel fasteners in the wood, especially if the wood is treated with preservatives. In buildings, metal fasteners are often the coldest surfaces, encouraging condensation and corrosion.

Energy Efficiency

Moisture can significantly degrade the thermal performance of most insulation materials. Moisture contributes to heat transfer in both sensible and latent forms, as well as through mass transfer. The effect depends on the type of insulation material, moisture content, temperature of the insulation material and its thermal history, the location of moisture in the insulation material, and the building envelope's interior and exterior environments. Reported relationships between thermal performance of the insulation material and moisture content vary significantly. Kyle and Desjarlais (1994) estimated that water distribution accounts for a difference of up to 25% in heat flux in some cases. Evaporation on the warm side and condensation or adsorption on the cold side add important latent heat components to the heat flux (Kumaran 1987).

Hedlin (1988) and Shuman (1980) experimentally showed that, for building envelopes containing permeable fibrous insulations that were undergoing temperature reversals, the heat flux transferred by that moisture drive increased sharply as the moisture content increased to approximately 1% by volume. The rate of heat transfer increase diminished rapidly with further increases in moisture content. Heat transfer for permeable insulation with 1% moisture content by volume was roughly double that of dry insulation. Pedersen-Rode et al. (1991) analytically reproduced Hedlin's results. They demonstrated the high mobility of moisture in a permeable insulation and showed that latent effects are appreciable for a wide variety of North American climates. Latent effects typically add to the building's energy load and can increase peak energy demand. The extra load is added in the warm afternoon, and nearly the same amount of heat is removed in the cool evening.

Under conditions where water vapor pressure gradients change slowly or where the insulation layer has an extremely low water vapor permeance, little water vapor is transported, but moisture still affects sensible heat transfer in the building envelope component. Epstein and Putnam (1977) and Larsson et al. (1977) showed a nearly linear increase in sensible heat transfer of approximately 3 to 5% for each volume percent increase in moisture content in cellular plastic insulations. For example, an insulation material with a 5% moisture content by volume has 15 to 25% greater heat transfer than when dry. Other field studies by Dechow and Epstein (1978) and Ovstaas et al. (1983) showed similar results for insulations installed in below-grade applications such as foundation walls.

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