CHAPTER 23

THERMAL AND MOISTURE CONTROL IN INSULATED 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 performance. This chapter deals with heat, air, and moisture transfer definitions; flow calculations for heat, vapor, air, and water; and the fundamentals of combined heat, air, and moisture movement as it relates to envelope components. The chapter also discusses thermal insulation materials and airflow and vapor retarders.

TERMINOLOGY AND SYMBOLS

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

Heat

Specific heat capacity c is the change in heat (energy) of unit mass of material for unit change of temperature in J/(kg·K).

Volumetric heat capacity ρc is the change in heat stored in unit volume of material for unit change of temperature, in J/(m³·K).

Heat transfer, in W, is the transfer of energy induced by a temperature difference, and may occur by conduction, convection, radiation, mass transfer, or any combination.

The vector **heat flux** q is the time rate of heat transfer through a unit area, in W/m².

Thermal conductivity *k* 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 $W/(m \cdot K)$. 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 25 for more detail).

SIMPLIFIED HYGROTHERMAL DESIGN

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Thermal resistivity R_u is the reciprocal of thermal conductivity. Units are $(m \cdot K)/W$.

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 $W/(m^2 \cdot K)$.

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 Table 4 of Chapter 25.

Thermal diffusivity α is the ratio between (apparent) thermal conductivity and volumetric heat capacity, in m²/s.

Heat transfer film coefficient or surface film conductance h_i or h_o is heat transferred by convection and radiation between a 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 W/(m²·K). (Subscripts *i* and *o* often denote inside and outside film coefficients, respectively.)

Surface film resistance R_i or R_o is the reciprocal of the heat transfer film coefficient, in (m²·K)/W. (Subscripts *i* and *o* often denote inside and outside surface film resistances and conductances, respectively.) 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 resistance *R* is the mean temperature difference between two defined surfaces of material or construction under steadystate conditions that induces a unit heat flux in $(m^2 \cdot K)/W$. Thermal resistance is the reciprocal of the thermal conductance.

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 W/(m² · K). Thermal transmittance is

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sometimes called the *overall coefficient of heat transfer* or 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. Table 2 in Chapter 25 lists values of E for various air spaces.

Surface reflectance ρ is the fraction of the radiant flux falling on a surface that is reflected.

Air

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

Air flux m_a , a vector, is the time rate of air transfer through a unit area, in kg/(m²·s).

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 kg/(m²·s·Pa), kg/(m·s·Pa), or kg/(s·Pa).

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 kg/(m·s·Pa) or s.

Moisture

Moisture content w is the amount of moisture per unit volume of porous material, in kg/m³.

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 capacity ξ is the change in stored moisture per unit weight of porous material and per unit difference in suction, 1/kPa.

Volumetric moisture capacity $\rho\xi$ is the change in stored moisture per unit volume of porous material and per unit moisture potential change (kg/m³·kPa).

Water vapor transfer M_{ν} is the water vapor flow induced by a partial water vapor pressure difference or a flow of humid air, in kg/s.

Water vapor flux m_v is the time rate of water vapor transfer through a unit area, in kg/(m²·K). Vapor flux is a vector.

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 kg/(m²·s·Pa).

Water vapor permeability μ 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 kg/(m·s·Pa). 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 $(m^2 \cdot s \cdot Pa)/kg$.

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

Moisture flux m_m , a vector, is the time rate of moisture transfer through a unit area, in kg/(m²·s).

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 kg/(m·s·Pa) (suction).

Moisture diffusivity D_m is the ratio between the moisture permeability and the volumetric moisture capacity, in m²/s.

HEAT TRANSFER

As explained in Chapter 3, heat transfer by apparent conduction in a solid is governed by Fourier's law:

$$q = -k \operatorname{grad}(t)$$
 or $q = -k dt/dx$ (1)

where

q = heat flux (for a unit area)

 \hat{k} = apparent thermal conductivity

grad(*t*) = gradient of temperature (i.e., change in temperature per unit length, perpendicular to isothermal surfaces in the solid)

dt/dx = gradient of temperature along x axis, assuming orientation of direction of flow along x axis; identical to grad(t) when x axis is selected as flow direction

For homogeneous, isotropic solids, substituting Equation (1) into the relationship for conservation of energy yields

$$\frac{\partial t}{\partial \tau} = \alpha \left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} \right) = \alpha \nabla^2 t \tag{2}$$

where

 α = thermal diffusivity of solid

 $\tau = time$

 ∇^2 = Laplace operator

STEADY-STATE THERMAL RESPONSE

In steady state, Equation (2) reduces to

$$\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} = 0$$
(3)

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:

$$R = R_1 + R_2 + R_3 + R_4 + \dots + R_n \tag{4}$$

where

 R_1, R_2, \ldots, R_n = resistances of individual layers, (m²·K)/W

R = resistance of building assembly surface to surface, (m²·K)/W

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, the surface film resistances R_i and R_o must be added to R.

Surface Film Resistances

The surface film resistance and its reciprocal, the heat transfer film coefficient, include the heat transfer to or from a surface by the combined effect of radiation, convection, and conduction. Each transport mode can vary independently. 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. Table 1 illustrates the effect of temperature of the surrounding surfaces on the surface heat flux by radiation. Heat transfer by convection is controlled by surface roughness, air movement, and temperature difference between the air and surface. Usually, because the surface-to-surface thermal resistance of a wall is high

Surrounding Surface		Surface	Heat Flu	x, W/m ²	
Temperature, °C	23.9	21.1	18.3	15.6	10
Convection	20.8	20.8	20.8	20.8	20.8
Radiation	13.9	27.1	40.4	53.6	78.6
Total	34.7	47.9	61.2	74.4	99.4

Table 1Variation in Surface Heat Flux for Vertical Surfacesat 26.7°C with Different Temperatures of Surrounding Surface(21.1°C Ambient Still Air; 0.83 Emittance)

compared with the surface film resistances, an exact value is of minor importance. However, on a single pane of glass, for example, they constitute almost the entire resistance.

Raber and Hutchinson (1945) analyzed the factors affecting the heat transfer film coefficient. The convective part is markedly dependent on the nature of air movement on the surface, as illustrated by Figure 1 in Chapter 25. On smooth surfaces, surface length also affects convection, with the average value decreasing as surface length increases (Parmelee and Huebscher 1947). Observations of the magnitude of low-temperature radiant energy from outdoor surroundings show that only under certain conditions can the outdoors be treated as a blackbody radiating at an effective air temperature (Parmelee and Aubele 1950).

Thus, selecting a building's heat transfer film coefficients is a matter of judgment. The values given in Table 1 in Chapter 25 apply to common building components. In special cases, where heat transfer film coefficients become important factors in the overall heat flux transferred, more accurate values may be required. In such cases, use the principles and data in Chapter 3.

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. In all cases, 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 3 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 25 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 vary independently of each other.

Table 3 in Chapter 25 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.

For narrow air spaces, defined as those for which the product of the temperature difference (K) and the cube of the space thickness (mm) is less than 27 000 for heat flow horizontally or downward and less than 9000 for heat flow upward, convection is practically suppressed and the Nusselt number turns to 1. The conductance for these spaces is the sum of the radiative conductance and heat conduction through air. Both components can be computed by the method shown in the footnotes to Table 3 in Chapter 25. Effects of different mean temperatures, temperature differences, and effective emittances may be found in the table.

Low-emittance windows are exemplary of the high thermal resistance presented by a narrow space filled with a gas with very low thermal conductivity and with low-emittance surfaces. To obtain high thermal resistance with reflective insulation, a series of multiple air layers bounded by reflective surfaces is needed. The total resistance then equals the sum of resistances across each air space. All air layers or spaces must be sealed because air moving between the layers can greatly increase heat flow. Depending on the type of reflective insulation, one or both sides may have highly reflective surfaces. Except for thick horizontal air spaces with heat flow down, little is gained thermally by adding a second highly reflective surface to the same air space. If an air space has only one reflective surface and is completely dry, the side on which the reflective surface is placed makes no difference in the rate of heat transfer. In typical building situations, however, water vapor is present and the reflective facing should be placed on the warm side of the air space; otherwise, condensation can increase the emittance and reduce the insulation value (see Table 2 in Chapter 25).

For reflective insulation used with heating and air conditioning, the emittance value for long-wave (infrared) radiation is important, not the value for the shorter wavelengths of the visible spectrum. Visible brightness is not a measure of the reflectance for long-wave radiation because reflectances for light and for long wavelengths are unrelated. Chemical action, dust, or the presence of condensation or frost can change a reflective surface enough to reduce its reflectance and increase its emittance. Chemical changes include oxidation, corrosion, or tarnishing caused by air, moisture, wet plaster, or the chemical treatment of wood spacing strips or other adjoining structural members.

Total Thermal Resistance of a Flat Building Component

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

$$R_T = R_i + R + R_o \tag{5}$$

where

$$R_i$$
 = thermal resistance of indoor air film, (m²·K)/W

 R_o = thermal resistance of outdoor air film, (m²·K)/W

For a wall that includes an air space of conductance *C*, the overall resistance is

$$R_T = R_i + R_1 + \frac{1}{C} + R_2 + R_o$$
(6)

where

- R_1 = thermal resistance of layer at one side of air space, (m²·K)/W
- R_2 = thermal resistance of layer at other side of air space, (m²·K)/W

Thermal Transmittance of a Flat Building Component

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

$$U = \frac{1}{R_T} \tag{7}$$

Calculating thermal transmittance requires knowing the (1) apparent thermal conductivity and thickness of all homogeneous layers, (2) thermal resistance of the nonhomogeneous layers, (3) surface film resistances at both sides of the construction, and (4) conductance of air spaces in the construction.

Interface Temperatures in a Flat Building Component

The temperature drop through any layer of a wall is proportional to its resistance. Thus, the temperature drop Δt_j through R_j in Equation (4) is

$$\Delta t_j = \frac{R_j(t_i - t_o)}{R_T} \tag{8}$$

where t_i and t_o are the indoor and outdoor reference temperatures, in °C.

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

$$t_{j} = t_{o} + \frac{R_{o}^{j}}{R_{T}}(t_{i} - t_{o}) = t_{o} + R_{o}^{j}q$$
(9)

where

 $R_o^j =$ sum of thermal resistances between inside and interface *j* in flat component, (m²·K)/W

q = heat flux through flat component, W/m²

If the apparent thermal conductivity of the 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 (5) or (6) and the temperature at each interface using Equation (10). 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.

Heat Flow Through a Flat Building Component

Equation (10) gives the heat flux through a flat building component:

$$q = \frac{t_i - t_o}{R_T} \tag{10}$$

where

- R_T = total thermal resistance as given by Equation (5) or (6), (m²·K)/W
- t_i, t_e = inside and outside reference temperatures, °C

Series and Parallel Heat Flow Paths

In many installations (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 using Equations (5), (6), and (7). The average transmittance of the wall is then

$$U_{av} = aU_a + bU_b + \dots + nU_n \tag{11}$$

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

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 by Equation (5) or (6) and the results weighted by contributing surface area.

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 25).

Thermal Bridges and Whole-Wall Thermal Transmittance

In some 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 25. Two- and threedimensional thermal bridging estimates require the use of appropriate computer modeling tools.

TRANSIENT THERMAL RESPONSE

Steady state represents the average thermal response and is the appropriate form of analysis in buildings with low thermal mass. However, in climates where daily temperature swings oscillate about a comfortable mean temperature, transient analysis is appropriate. Methods of transient analysis include time constant or transfer functions, both of which demand a finite element or finite volume calculation.

Using harmonic analysis, the temperature damping, periodic thermal resistance, and thermal admittance of a flat component with constant properties can be calculated, leading to good estimates of transient performance. The assumptions that must be made are that the inside and outside temperatures vary harmonically, the period is known, and the assembly is the only barrier between the inside and the outside, with the thermal effect of both environments represented by a surface film coefficient. All three characteristics are represented as complex numbers. The amplitude represents the damping effect, and the argument represents the time shift.

Transient performance can be approximated by downgrading a flat component to a resistance-capacitance-resistance network. Solutions to the balance equation can be found in heat transfer references, such as Carslaw and Jaeger (1986).

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 27 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

$$m_a = -k_a \operatorname{grad}(P_a) \tag{12}$$

where

 k_a = air permeability of open porous material

 $grad(P_a) = gradient in total air pressure (stack, wind, and mechanical systems)$

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

$$m_a \text{ or } M_a = C(\Delta P_a)^n$$
 (13)

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.

MOISTURE FLOW

MOISTURE PROBLEMS IN BUILDINGS

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 nonporous surfaces.

Visible and invisible degradation as a consequence of moisture absorption and wetting 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.

Mold, Dust Mites, and 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 the 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, 1999). 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 5°C. Moisture accumulation below 5°C 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 5°C. A mathematical model for predicting a mold growth index was developed by Hukka and Viitanen (1999) and successfully linked to a hygrothermal model by Karagiozis and Salonvaara (1998).

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, and soft furniture).

Paint Failure and Other Appearance Problems

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

Structural Failures

Structural failures caused by wood decay are rare but have occurred (e.g., Merrill and TenWolde 1989). Decay generally requires wood moisture content at fiber saturation (usually about 30%) or higher and temperatures between 10 and 40°C. Such high wood moisture contents are possible in green lumber or by absorption of liquid water from condensation, leaks, ground water, 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 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.

Effect of Moisture on Heat Flow

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 Moisture Content and Heat Flow section of the Bibliography lists numerous works that have investigated the effect of moisture content on heat flow. They show that 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. The 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 certain 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).

Shuman (1980) and Hedlin (1988) 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.

Moisture Effect on Heat Storage

Moisture also affects the specific heat capacity of some hygroscopic building materials. At 10% moisture content, nearly 30% of the specific heat capacity of wood is in the water held in the cell walls. Because the specific heat capacity of wood is a function of its temperature and moisture content (but almost independent of density and species), heat storage calculations must include an estimate of the equilibrium in-service moisture content.

MOISTURE 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 (rh) 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. 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 sometimes referred to as the capillary moisture content. Figure 1 shows typical sorption curves, giving the equilibrium moisture content as a function of relative humidity. The equilibrium moisture content increases with relative humidity, especially above 80%. It decreases slightly with increasing temperature.

Chapter 22 describes hygroscopic substances and their use as dehumidifying agents. Table 2 in Chapter 12 of the 2003 ASHRAE



Fig. 1 Adsorption Isotherms for Wood, Concrete, and Gypsum

Handbook—HVAC Applications has data on the moisture content of various materials in equilibrium with the atmosphere at various relative humidities.

Wood and many other hygroscopic materials change dimensions with variations in moisture content. At fiber saturation, the cell walls of wood are saturated but no free water exists in cell cavities. It represents the upper limit for moisture gain from the air as water vapor, as well as the upper limit of swelling. Although more water can be absorbed in cell cavities, additional swelling does not occur. Wood moisture content is expressed as a percentage of its oven-dry mass. The fiber saturation point for most species is about 30%. The average equilibrium moisture content at 20°C and 45% rh (heating-season indoor conditions) is about 8.5%. At 24°C and 70% rh (summer conditions), equilibrium moisture content is about 13%.

The resulting dimensional changes in wood are proportional to the change in moisture content, but vary with species and direction of grain. For white oak, which is representative of interior trim material, 4.5% moisture content variation causes 2.5% volumetric shrinkage or swelling. Longitudinal dimensional change in straight-grained wood is insignificant, but it increases with crossgrain and other irregularities. Accordingly, residential wood trusses with top and bottom chords exposed to different temperature and moisture regimes may show measurable seasonal vertical movements (Plewes 1976).

Thermal expansion of wood is outweighed by shrinkage or swelling due to these moisture content changes. The linear thermal expansion coefficient across the grain ranges from about 12.6×10^{-6} per kelvin for light wood to about 45×10^{-6} per kelvin for dense wood, which is small compared to many other materials. The thermal expansion coefficient parallel to the grain is between 3.1×10^{-6} and 4.5×10^{-6} per kelvin.

Most plant and animal fibers undergo dimensional changes similar to those noted in wood. Typical values for wood can be found in Table 2; the *Wood Handbook* (FPL 1999) gives more detailed information. Related changes in other materials are not as well documented. However, different expansion rates caused by temperature and moisture changes in different materials used in composite constructions should be considered (Baker 1964; BRS 1974).

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 the capillary moisture content.

Wood Species	Radial %	Tangential %	Volumetric %
Hardwoods			
Birch, Yellow	7.3	9.5	16.8
Oak			
Northern red	4.0	8.6	13.7
Southern red	4.7	11.3	16.1
White	5.6	10.5	16.3
Softwoods			
Cedar			
Northern white	2.2	4.9	7.2
Western red cedar	2.4	5.0	6.8
Douglas fir, Coast	4.8	7.6	12.4
Fir, White	3.3	7.0	9.8
Hemlock, Western	4.2	7.8	12.4
Pine			
Eastern white	2.1	6.1	8.2
Longleaf	5.1	7.5	12.2
Ponderosa	3.9	6.2	9.7
Redwood, Young growth	2.2	4.9	7.0
Imported wood			
Lauan	3.8	8.0	

 Table 2
 Linear and Volumetric Shrinkage Values of Wood, from Green to Oven-Dry Moisture Content

Note: Values expressed as a percentage of the green dimension (FPL 1999).

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
- · Capillary suction of liquid water in porous building materials
- · Liquid flow by gravity or air pressure gradients

In the past, moisture control strategies focused on water vapor diffusion only. Displacement of water vapor by air movement was treated superficially, and water supplied 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 the highest priority in moisture control.

Liquid flow by gravity and air 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 Kuenzel (1995) and Kumaran et al. (1994). For a discussion of water vapor in air, see Chapter 6, Psychrometrics.

Water Vapor Flow by Diffusion

Water vapor migrates by diffusion through air and building materials, normally in very 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):

$$m_{\nu} = -\mu \operatorname{grad}(p) \tag{14}$$

where

- grad(p) = gradient of partial water vapor pressure (i.e., change of partial water vapor pressure per unit length along a path perpendicular to isobaric surfaces)
 - μ = water vapor permeability

According to Equation (14), 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. Water vapor permeability is a function of relative humidity and temperature, and may vary spatially because of variations in the material's porous system.

Test methods for measuring water vapor permeability are described in ASTM *Standard* E96, Standard Test Methods for Water Vapor Transmission of Materials. Water vapor flux through a material is determined gravimetrically while maintaining constant temperature and partial water vapor pressure differential across the specimen. The standard identifies two tests: a dry cup (0 to 50% relative humidity) and a wet cup (50 to 100% relative humidity).

Permeability is usually expressed in kg/($m \cdot s \cdot Pa$) and permeance in kg/($m^2 \cdot s \cdot Pa$). 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 50 mm thick generally is assumed to have half the permeance of a 25 mm 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 plywood or gypsum board with paper facings.

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.

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

$$m_v = W m_a \approx \frac{0.62}{P_a} m_a p \tag{15}$$

where

$$W =$$
 humidity ratio of moving air

 $m_a = \text{air flux}$

p = partial water vapor pressure in air

 P_a = atmospheric air pressure

Even small air fluxes can carry large amounts of water vapor when compared to vapor diffusion.

Water Flow by Capillary Suction

Within small pores of an equivalent diameter less than 0.1 mm, molecular attraction between the surface and the water molecules causes capillary suction, defined as

$$s = \frac{2\sigma\cos\theta}{r} \tag{16}$$

where

s = capillary suction

 σ = surface tension of water

r = equivalent radius of capillary θ = contact wetting angle

0 = contact wetting angle

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:

$$m_m = -k_m \operatorname{grad}(s) \tag{17}$$

where

 m_m = moisture flux k_m = water permeability

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.

The term *moisture* includes both vapor and liquid. In a capillary opening, isothermal and nonisothermal moisture flow occurs in the liquid and vapor phases if the capillaries are not completely waterfilled. Transfer in the vapor phase by diffusion is caused by a difference in vapor saturation pressure in the capillaries. Kelvin's formula (Kuenzel 1995) states that the saturation water vapor pressure in equilibrium with suction in a capillary is given by

$$p'' = p' \exp\left(\frac{s}{\rho_w RT}\right) = p' \exp\left(\frac{2\sigma\cos\theta}{r\rho_w RT}\right)$$
(18)

where

p'' = saturation vapor pressure in capillary

p' = saturation vapor pressure in ambient air at a same temperature as p''

 ρ_w = density of water

R = ideal gas constant for water vapor

T = absolute temperature, K

Equation (18) shows that saturation water vapor pressure is lower in smaller capillaries than in larger, which causes vapor to diffuse from the larger water-filled capillaries to the smaller ones. Saturation water vapor pressure in capillaries is also lower at lower temperatures, which causes diffusion from higher to lower temperatures.

Equation (18) can be rewritten as

$$s = \rho_w RT \ln \phi \tag{19}$$

where ϕ is the relative humidity of air in the pores.

Isothermal Moisture Flow

It is nearly impossible to experimentally distinguish between liquid flow by suction and water vapor flow by diffusion in open porous, hygroscopic materials. Because these materials have a very complex porous system and each surface is transversed by liquidfilled pore fractions and vapor-filled pore fractions, vapor and liquid flow are 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

$$\frac{\partial w}{\partial t} = -\operatorname{div}(m_v + m_w) + S_w \tag{20}$$

where

- w = moisture content of building material
- m_v = water vapor flux

 m_w = liquid water flux

- S_w = moisture source or sink
- div = divergence (resulting inflow or outflow per unit volume of solid)

Vapor and liquid fluxes are given by Equations (14) and (17), which, under isothermal conditions, may be rewritten in terms of a single driving force *s* or ϕ :

$$m_v = -\mu \operatorname{grad}(p) = -\mu p_{sat} \operatorname{grad}(\phi) = -\frac{\mu \phi}{\rho_w RT} \operatorname{grad}(s)$$
 (21)

$$m_w = -k_m \text{grad}(s) = -k_m \frac{\rho_w RT}{\phi} \text{grad}(\phi)$$
(22)

The sum of the liquid and vapor transport coefficients in Equations (21) and (22) are denoted k_{ϕ} if relative humidity is used as a driving force and k_s if suction is used.

The isothermal moisture flow equation is

$$m_m = -k_s \operatorname{grad}(s) = -k_\phi \operatorname{grad}(\phi) \tag{23}$$

where

 m_m = moisture flux

 k_s = moisture permeability (related to suction)

 k_{ϕ} = moisture permeability (related to relative humidity)

Nonisothermal Moisture Flow

In nonisothermal conditions, temperature acts as a second driving force. Its effect on liquid flow is minor, but may be significant on vapor flow. The nonisothermal moisture flow equation is

$$m_m = -k_s \operatorname{grad}(s) - k_T \operatorname{grad}(T) \tag{24}$$

$$m_m = -k_{\phi} \operatorname{grad}(\phi) - k_T \operatorname{grad}(T)$$
(25)

where

or

 $m_m =$ moisture flux

 $\vec{k_T}$ = thermal moisture permeability

Other potentials can be used. The only restriction is that two potentials are needed to describe nonisothermal moisture flow. When other potentials are used, the material properties appropriate to those potentials must be used.

COMBINED HEAT, AIR, AND MOISTURE FLOW

Air leakage through building components may increase ventilation in a building beyond the value needed for comfort and indoor air quality (see Chapter 27). However, air also carries heat. The consequences of that convective heat flux may be detrimental for thermal performance. 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 Ufactor by a factor of 2.5 or more.

Airflow changes the assumption at the basis of Equation (2) that no mass flow develops in the solid. The sensible heat flux that moves together with the air is

$$q = c_a m_a t \tag{26}$$

where c_a is the specific heat capacity of air.

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 (1996a, 1996b) 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. Karagiozis and Kuenzel (1999) provided an update on the more sophisticated tools, indicating both the capabilities and the limitations. Also, the ASTM manual, *Moisture Analysis and Condensation Control in Building Envelopes* (Trechsel 2001), provides an update on existing tools and approaches to investigate the terms of heat, air, and moisture transport performance of building envelope systems.

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 in such a process.

The features of a complete moisture analysis model include

- Transient heat, air, and moisture transport formulation, incorporating the physics of
 - Airflow
 - Water vapor transport by advection (combination of water vapor diffusion and air-driven vapor flow)
 - Liquid transport by capillary action, gravity, and pressure differences
 - Heat flow by apparent conduction, convection, and radiation
 - Heat and moisture storage/capacity of the materials
 - Condensation and evaporation processes with linked latent-tosensible heat transformation
 - Freezing and thawing processes with linked latent-to-sensible heat transformation and based on the laws of conservation of heat, mass, and momentum.
- A one-, two-, or three-dimensional spatial formulation of the building component. For airflow assessment, that formulation should be very detailed, including air leaks, cracks, voids, air spaces, and cavities.
- Material properties as functions of moisture content, relative humidity, and temperature:
 - · Density
 - · Air properties: permeability and permeance
 - Thermal properties: specific heat capacity, apparent thermal conductivity, Nusselt numbers, and long-wave emittance (for cavities and air spaces)
 - Moisture properties: porosity, sorption curve, water retention curve, vapor permeability, water permeability, or liquid diffusivity
- Boundary conditions (generally on an hourly basis)
 - · Outside temperature and relative humidity
 - Incident short-wave solar and long-wave sky radiation (depending on inclination and orientation)
 - · Wind speed, orientation, and pressure
 - Wind-driven rain at exterior surfaces (depending on location and aerodynamics)
 - Interior temperature, air pressure excess, relative humidity (or interior moisture sources and ventilation flows), and air stratification
- Surface conditions
 - Heat transfer film coefficients (combined convection and radiation, separate for convection and radiation)
 - Mass transfer film coefficients
 - Short-wave absorptance of the exterior surface
 - · Long-wave emittance of the exterior surface
- 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, introduce an additional capillary resistance, or behave as a real contact.

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, air pressure; temperature; moisture content; relative humidity; and air, heat, and moisture fluxes are common outputs. 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 a 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 model to estimate the rate of mold growth and corrosion was developed by Karagiozis and Kuenzel (1999). Nofal and Kumaran (1999) assessed the durability of wood-frame construction using the concept of damage functions. It is expected that hygrothermal models will be incorporated in whole-building simulation tools (Karagiozis and Salonvaara 1999a).

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 threedimensional 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 not yet been established, although work is under way on ASHRAE Standard 160, Design Criteria for Moisture Control in Buildings. More extensive data on material properties are becoming available (e.g., ASHRAE Research Project RP-1018; Kumaran 1996), 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 existing tools' capabilities. In such cases, simple qualitative schemes and field tests still are the way to proceed.

SIMPLIFIED HYGROTHERMAL DESIGN CALCULATIONS AND ANALYSES

SURFACE CONDENSATION

Surface condensation occurs when water vapor comes in contact with a 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.

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

$$f_{h_i} = \frac{t_s - t_o}{t_i - t_o}$$
(27)

where

 t_s = surface temperature on warm side

 t_o = ambient temperature on cold side

 t_i = ambient temperature on warm side

The minimum temperature ratio to avoid surface condensation is

$$f_{h_i,min} = \frac{t_{d,i} - t_o}{t_i - t_o}$$
(28)

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

For flat components, the temperature ratio can be stated as

$$f_{h_i} = \frac{R_{si}^o h_i}{1 + R_{si}^o}$$
(29)

where

 R_{si}^{o} = thermal resistance between surface on warm side and cold ambient

 h_i = heat transfer film coefficient at warm side

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

$$L_{min} = k \left[\frac{f_{h_i,min}}{h_i(1 - f_{h_i,min})} - R_{add} \right]$$
(30)

where R_{add} is the thermal resistance between the surface on the warm side and the cold ambient for the wall without thermal insulation.

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. The change in phase from vapor to bound or sorbed water occurs at energies quite different from the energies of condensation. Nevertheless, the term "condensation" is used in the following examples 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, remember that water vapor permeances may vary with relative humidity and that rain splash, flashing imperfections, leaky or poorly formed joints, rain exposure, airflow, and sunshine can have overriding effects. Hens (1978) and Vos and Coelman (1967) upgraded the Glaser method to account for moisture accumulation and drying. 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 here, with two examples of its use. A comprehensive description of the dewpoint and the Glaser method 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

$$m_v = -\mu \frac{\Delta p}{d} = -\frac{\Delta p}{Z} \tag{31}$$

where

 m_v = water vapor flux through layer of material, ng/(s·m²)

 Δp = partial water vapor pressure difference across layer, Pa

 μ = water vapor permeability of material, ng/(Pa · m · s)

d = thickness of layer, m

Z = water vapor resistance, (Pa · m² · s)/ng

The dew-point method can be summarized as follows:

- Select the building components. Determine, for each component, thickness, thermal resistance and water vapor diffusion resistance. See Tables 4 and 9 in Chapter 25. Select values for indoor and outdoor surface film resistance.
- Select indoor and outdoor temperature and humidity design conditions. Determine indoor and outdoor water vapor pressures. Determine total thermal resistance, total water vapor diffusion resistance, total temperature drop, and total vapor pressure drop.
- 3. Calculate temperature drops and interface temperatures.
- 4. Find water vapor saturation pressures corresponding to interface temperatures.
- 5. Calculate partial water vapor pressure drops and interface partial water vapor pressures.

Heat Conduction and Vapor Diffusion Properties of Wall				Calculated Temperature Drops, Surface Temperatures, and Saturation Water Vapor Pressures			Initial and Final Calculation of Water Vapor Pressure Drops and Surface Water Vapor Pressures			
Thermal		Vapor 1	Vapor Diffusion	Temperature	perature Interface	Interface Saturation	Vapor Pressure, Pa			
Air Film or Material	Resistance, (m ² ·K)/W	Permeance, ng/(s·m ² ·Pa)	Resistance, (Pa·m ² ·s)/ng	Drop, °C	Temperature, °C	Vapor Pressure, Pa	In Calcı	itial ılation	Fiı Calcu	nal lation
					21	2488		996		996
Surface film coefficient	0.12	9200	0.00011	1.4			2		13	
~					19.6	2289		994		983
Gypsum board, painted,	0.079	290	0.0035	0.9	10 7	21.65	74	0.20	433	550
cracked joints	1.0	1700	0.00050	21.6	18.7	2165		920	70	550
Insulation, mineral fiber	1.9	1700	0.00058	21.6	2.0	470	11	000	72	470
Diversion of shoething	0.11	20	0.0245	12	-2.9	478	772	909	200	4/8
Fiywood sheatillig	0.11	29	0.0345	1.5	4.2	430	123	186	299	170
Wood siding	0.18	2010	0.0005	21	-4.2	450	11	100	4	1/)
wood slaing	0.10	2010	0.0005	2.1	-6.3	361		175		175
Surface film coefficient	0.03	57 000	0.000017	0.3			0		0	
					-6.6	350		175		175
Total	2.42		0.03606							

Table 3	Data f	or Example 1	L
---------	--------	--------------	---

6. Check whether the partial water vapor pressure is below saturation at all interfaces. If so, no condensation is indicated and vapor flow through the wall may be determined if desired. If condensation is indicated, then continue on to steps 7 to 9.

- 7. Find the condensation surface (the interface where the difference between calculated partial water vapor pressure and water vapor saturation pressure is highest). Set partial water vapor pressure at that interface equal to the saturation water vapor pressure.
- 8. Recalculate the partial water vapor pressures in all interfaces. If any partial water vapor pressure is again above saturation, repeat steps 5 and 6 with the interface where the difference p - p' is the highest now as additional condensation interface.
- 9. If needed, calculate water accumulation rates.
- **Example 1.** A wood-framed wall is constructed of the materials described in Table 3. Assume monthly mean conditions of 21°C, 40% rh indoors and -6.7°C, 50% rh outdoors. Indoor and outdoor vapor pressures are 2.4980 kPa and 0.3472 kPa, respectively.

Solution:

Step 1. Calculate the temperature drop across each layer. The temperature drop is proportional to the R-value:

$$\frac{\Delta t_{layer}}{t_i - t_o} = \frac{R_{layer}}{R_T}$$

Table 3 lists the resulting temperature drops and resulting temperatures at each interface.

Step 2. Find the saturation water vapor pressure corresponding to the interface temperatures (Table 3). These values can be found in Table 2 in Chapter 6.

Step 3. Calculate the water vapor pressure drops across each layer. These are calculated the same way as the temperature drops in step 1:

$$\frac{\Delta p_{layer}}{p_i - p_o} = \frac{Z_{layer}}{Z_T}$$

where

 Z_T = total water vapor diffusion resistance of wall (the sum of the diffusion resistances of all layers), (Pa·m²·s)/ng

p = partial water vapor pressure, Pa

From Table 3, the total water vapor diffusion resistance of the wall without the vapor retarder is

$$Z_{wall} = \frac{1}{9200} + \frac{1}{290} + \frac{1}{1724} + \frac{1}{29} + \frac{1}{2010} + \frac{1}{57} 000$$
$$= 0.0391 \text{ (Pa} \cdot \text{m}^2 \cdot \text{s)/ng}$$

The partial water vapor pressure drop across the whole wall is calculated from the indoor and outdoor saturation water vapor pressures and relative humidities (see Table 3).

$$p_{wall} = p_i - p_o = (40/100)2496 - (50/100)370 = 813$$
 Pa

Table 3 lists the water vapor pressure drops in the initial calculation column.

Step 4. Figure 2 shows the calculated saturation and partial water vapor pressures. Comparison reveals that the calculated partial water vapor pressure on the interior surface of the sheathing is well above saturation at that location. This indicates condensation, probably on the surface of the sheathing, not within the insulation. If the location of condensation and the condensation rate are of interest, two additional steps are necessary.

Step 5. Figure 2 shows that the calculated water vapor pressure exceeds the saturation water vapor pressure by the greatest amount at the back side of the sheathing. Therefore, this is the most likely location for condensation. With condensation, the water vapor pressure should equal the saturation water vapor pressure at that interface (see the final calculation column in Table 3).

Step 6. The change of water vapor pressure on the plywood sheathing alters all other partial water vapor pressures as well as water vapor flux through the wall. Calculating partial water vapor pressures is similar to the calculation in step 3, but the wall is now divided in two parts: one on the interior of the condensation interface (i.e., gypsum board and insulation) and the other on the exterior (plywood sheathing and wood siding). Water vapor pressure drop over the first part of the wall is

$$\Delta p_1 = 996 - 478 = 518$$
 Pa

That over the second part is

$$\Delta p_2 = 478 - 175 = 303$$
 Pa

The diffusion resistances of both parts of the wall are

 $Z_1 = 1/9200 + 1/290 + 1/1724 = 0.0041 \text{ (Pa} \cdot \text{m}^2 \cdot \text{s)/ng}$

 $Z_2 = 1/29 + 1/2010 + 1/57\ 000 = 0.035\ (Pa \cdot m^2 \cdot s)/ng$

The water vapor pressure drops across each material can be calculated from the part between the inside and sheathing:

$$\frac{\Delta p_{layer}}{p_i - p'_{sheathing}} = \frac{Z_{layer}}{Z_s^{sheathing}}$$

and the part between the sheathing and outside:



Fig. 2 Dew-Point Calculation in Wood-Framed Wall (Example 1)

 Table 4
 Heat Conduction and Vapor Diffusion Properties of the Wall (Example 2)

Air Film or Material	Thermal Resistance <i>R</i> , (m ² ·K)/W	Vapor Permeance, perm ng/(s·m ² ·Pa)	Vapor Diffusion Resistance, rep (Pa·m ² ·s)/ng
Surface film coefficient	0.12	9200	0.00011
Gypsum board, painted, cracked joints	0.079	290	0.0035
Polyethylene foil	0	0.435	2.3
Insulation, mineral fiber	1.9	1700	0.00058
Plywood sheathing	0.055 (wet)) 29	0.0345
EIFS	1	72.5	0.0137
Stucco	0.01	185	0.0054
Surface film coefficient	0.03	57 000	0.000017
Total	3.25	N/A	2.323

$$\frac{\Delta p_{layer}}{p'_{sheathing} - p_o} = \frac{Z_{layer}}{Z^o_{sheathing}}$$

Final calculations of water vapor pressure (shown in Table 3) no longer exceed saturation, which means that the condensation plane was chosen correctly. Figure 2 shows the water vapor pressure profile (labeled "vapor pressure, final calculation"). However, vapor flux is no longer the same throughout the wall. The flux from inside increases, to the outside it decreases. The difference between both is the rate of moisture accumulation by interstitial condensation at the back side of the sheathing:

$$m_c = \frac{p_i - p'_{sheathing}}{Z_i^{sheathing}} - \frac{p'_{sheathing} - p_o}{Z_{sheathing}^o} = 1.15 \times 10^{-7} \text{ kg/(m}^2 \cdot \text{s})$$

This amounts to about 70 g/day per square metre. In this example, the plywood surface is below freezing, and this moisture accumulates as frost. Without freezing, the moisture content in the plywood would increase by 1% after about a week of condensation at this rate.

Dew-point analysis allows simple estimation of the effect of wall and roof cavity ventilation on heat and vapor transport by using parallel thermal and vapor diffusion resistances (TenWolde and Carll 1992; Trethowen 1979). These parallel resistances account for the heat and vapor that bypass the exterior material layers with the

Table 5	Calculated Temperature Drops, Surface
Temperatu	res, and Saturation Water Vapor Pressures
	in Winter (Example 2)

Air Film or Material	Temperature Drop, °C	Interface Temperature, °C	Interface Saturation Vapor Pressure, Pa
		21.0	2488
Surface film coefficient	1.0	21.0	2400
C	0.7	20.0	2337
cracked joints	0.7	19.3	2240
Polyethylene foil	0		
		19.3	2240
Insulation, mineral fiber	16.4	2.9	751
Plywood sheathing	0.5		
		2.4	726
EIFS	8.6		
~		-6.3	361
Stucco	0.1	6.25	259
Surface film coefficient	0.2	-6.35	358
Surface min coefficient	0.5	-6.6	350

ventilation air from outside. The equivalent thermal and water vapor diffusion resistances are determined from the following equations:

$$R_{par} = \frac{1}{m_a c_a} \tag{32}$$

$$Z_{par} = \frac{1}{m_a \xi}$$
(33)

where

 R_{par} = parallel equivalent thermal resistance, (K · m²)/W

- Z_{par} = parallel equivalent water vapor diffusion vapor flow resistance, (Pa·m²·s)/ng
- m_a = ventilation flux, kg/(m²·s)
- $\xi = 0.62/P_a$, where P_a is atmospheric pressure

Both equations of course only approximate the actual effect of ventilation.

Example 2. A timber-framed construction has a wet layer inside. The wall consists of the layers described in Table 3, including a 0.2 mm polyethylene membrane between the insulation and gypsum board. Instead of wood siding, it has an external insulation and finish system (EIFS), with 40 mm of expanded polystyrene as substrate and a spun glass reinforced stucco as finish (Table 4). If the plywood sheathing became soaked because of rain infiltration at the windows, how long would it take before the plywood reaches hygroscopic equilibrium after the leaks are sealed? Solve for two monthly mean conditions: winter, with 21°C, 40% rh indoors and -6.7°C, 50% rh outdoors.

Solution:

Steps 1 and 2 are the same as in Example 1. (See Tables 5 and 6.)

Step 3. Calculate the water vapor pressure drops across each layer, starting at the plywood sheathing at saturation pressure all over the thickness:

Between inside and sheathing:

$$\frac{\Delta p_{layer}}{p_i - p'_{sheathing}} = \frac{Z_{layer}}{Z_i^{sheathing}}$$

Table 6Calculated Temperature Drops, SurfaceTemperatures, and Saturation Water Vapor Pressuresin Summer (Example 2)

Air Film or Material	Temperature Drop, °C	Interface Temperature, °C	Interface Saturation Vapor Pressure, Pa
		25.0	3174
Surface film coefficient	0.08		
		24.9	3159
Gypsum board, unpainted,	0.05		
cracked joints		24.9	3150
Polyethylene foil	0		
		24.9	3150
Insulation, mineral fiber	1.19		
		23.7	2933
Plywood sheathing	0.03	aa 7	2025
FIEG	0.62	23.7	2927
EIFS	0.63	22.0	2010
C.	0.01	23.0	2819
Stucco	0.01	22.0	2010
Saufa an film an affiniant	0.02	23.0	2818
Surface film coefficient	0.02	22.0	2015
		23.0	2013

Table 7Calculation of Water Vapor Pressure Drops
and Surface Water Vapor Pressures in Winter
and Summer (Example 2)

	Vapor Pressure, Pa		
Air Film or Material	Winter	Summer	
	997	2221	
Surface film coefficient	997	2221	
Gypsum board, unpainted, cracked joints	996	2223	
Polyethylene foil	751	2933	
Insulation, mineral fiber	751*	2933*	
Plywood sheathing	726*	2927*	
EIFS	331	2241	
Stucco	551	2241	
Surface film coefficient	175	1971	
Surface min coefficient	157	1970	

*Saturation vapor pressure at surface temperature

Between sheathing and outside:

$$\frac{\Delta p_{layer}}{p'_{sheathing} - p_o} = \frac{Z_{layer}}{Z^o_{sheathing}}$$

From Table 4, the diffusion resistances of both parts of the wall are

 $Z_1 = 0.00011 + 0.0035 + 2.3 + 0.00058 = 2.304 (Pa \cdot m^2 \cdot s)/ng$

 $Z_2 = 0.0137 + 0.0054 + 0.000017 = 0.019 (Pa \cdot m^2 \cdot s)/ng$

Table 7 lists the water vapor pressure drops in the final calculation column.

Step 4. Figures 3 and 4 show the calculated saturation and partial water vapor pressures in winter and in summer. Comparison reveals that, in both cases, the calculated partial water vapor pressures between the sheathing and inside and the sheathing and outside are well below saturation. However, if outdoor relative humidity increases, if the stucco is very vapor-retarding, or if mineral fiber is used as EIFS, condensation may develop in the EIFS and at the back side of the stucco.



Fig. 3 Drying Wet Sheathing, Winter Situation (Example 2)



Fig. 4 Drying Wet Sheathing, Summer Situation (Example 2)

Step 5. Figures 3 and 4 show the calculated water vapor pressure in winter and in summer. Final calculations of water vapor pressure are shown in Table 7. The plywood is at water vapor saturation pressure; in no other interface is saturation reached. Figures 3 and 4 show the partial water vapor pressure profiles (labeled as vapor pressure). *Winter*

$$m_{sheathing,i} = \frac{p_i - p'_{sheathing}}{Z^{sheathing}} = 107 \text{ ng/(m}^2 \cdot \text{s})$$

$$m_{c,EIFS,stucco} = \frac{p'_{sheathing} - p_o}{Z^o_{sheathing}} = 28\ 817\ \text{ng/(m}^2 \cdot \text{s})$$

Summer

$$m_{sheathing,i} = \frac{p_i - p'_{sheathing}}{Z_i^{sheathing}} = -309 \text{ ng/(m}^2 \cdot \text{s})$$

$$m_{sheathing,o} = \frac{p'_{sheathing} - P_o}{Z^o_{sheathing}} = 50\ 068\ \text{ng/(m}^2 \cdot \text{s})$$

Drying consequently amounts to 77 g/m^2 per month in winter and to 1135 g/m^2 per month in summer. Plywood soaked with water can contain a moisture content excess up to 4.8 kg/m². Consequently, drying may take some 4 years.

THERMAL INSULATION MATERIALS

When properly applied, thermal insulation materials retard conductive, convective, and radiative heat flux. Thermal insulation in building envelopes does at least one of the following:

- · Conserves energy by reducing heat loss or gain of the building
- Controls surface temperatures for comfort
- Helps control the temperature of a building structure
- · Reduces the tendency for water condensation on surfaces
- Reduces temperature fluctuations in unconditioned or partly conditioned spaces

Thermal insulation materials may also serve additional functions, although these should be consistent with the capabilities of the materials and their primary purpose:

- · Adding structural strength to a wall, ceiling, or floor section
- Providing support for a surface finish
- Impeding water vapor transmission and air infiltration
- Preventing or reducing damage to structures from exposure to fire and freezing conditions
- Reducing noise and vibration

Poorly designed or improperly installed thermal insulation may promote moisture condensation and subsequent damage within a building envelope. When thermal insulation is used to control heat flow at all temperatures, the limiting value is its survival temperature.

BASIC MATERIALS

Thermal insulation normally consists of the following basic materials and composites:

- Inorganic, fibrous, or cellular materials such as glass, rock, or slag wool
- Calcium silicate, bonded perlite, vermiculite, and ceramic products (asbestos was also used, but its use has been discouraged or banned for several years; use caution if it is encountered in existing buildings)
- Organic fibrous materials such as cellulose, cotton, wool, wood, pulp, cane, or synthetic fibers, and organic cellular materials such as cork, foamed rubber, polystyrene, polyurethane, and other polymers
- Metallic or metallized organic reflective membranes, which must face an air-filled, gas-filled or evacuated space to be effective

PHYSICAL STRUCTURE AND FORM

Physical forms of building insulation include the following:

Loose-fill insulation consists of fibers, powders, granules, or nodules, usually poured or blown into walls or other spaces. **Insulating cement** is a loose material that is mixed with water or a suitable binder to obtain plasticity and adhesion. It is troweled or blown wet on a surface and dried in place. Both loose-fill and insulating cement are suited for covering irregular spaces.

Flexible and **semirigid insulation** consist of organic and inorganic materials with and without binders and with varying degrees of compressibility and flexibility. This insulation is generally available as blanket, batt, or felt, and in either sheets or rolls. Coverings and facings may be fastened to one or both sides and serve as reinforcing, airflow or vapor retarders (or both), reflective surfaces, or surface finishes. These coverings include combinations of laminated foil, glass, cloth or plastics and paper, or wire mesh. Although standard sizes are generally used, thickness and shape of insulation can be any convenient dimension.

Rigid materials are available in rectangular blocks, boards, or sheets, which are preformed during manufacture to standard lengths, widths, and thickness.

Reflective materials are available in sheets and rolls of singlelayer or multilayer construction and in preformed shapes with integral air spaces.

Formed-in-place insulations are available as liquid components or expandable pellets that can be poured, frothed, or sprayed in place to form rigid or semirigid foam insulation. Fibrous materials mixed with liquid binders can also be sprayed in place; in some products, the binder is also a foam.

Accessories for thermal insulation include mechanical and adhesive fasteners, exterior and interior finishes, vapor- and airflow-retarder coatings, sealants, lagging adhesives, membranes, and flashing compounds. ASTM *Standard* C168 defines terms related to thermal insulating materials.

PROPERTIES

A low apparent thermal conductivity is the primary property of a thermal insulation, but selecting a material may also involve secondary criteria (e.g., resiliency or rigidity, acoustical energy absorption, water vapor permeability, airflow resistance, fire hazard and fire resistance, ease of application, applied cost, health and safety aspects, or other parameters), which can affect the choice among materials that have almost equal thermal performance.

Apparent Thermal Conductivity

Thermal conductivity k is a property of a homogeneous, nonporous material. Most thermal insulation is porous and consists of combinations of solid matter with small voids, which comprise 90% or more of the volume. Heat transmission is therefore a combination of gas and solid conduction, radiation, and convection, and is affected by factors such as length of heat flow paths, temperature, temperature difference, and environmental conditions. In fact, a wide variety of physical, environmental, application, and, in some cases, aging factors affect the thermal performance of insulation. In some materials with low thermal conductivity (e.g., silica opacified aerogel, corkboard), heat transfer is almost purely conductive.

Although heat transmission characteristics are usually determined by measuring thermal conductivity, this property does not strictly apply to thermal insulation. A particular sample of a material has a unique value of thermal conductivity for a particular set of conditions. This value may not be representative of the material at other conditions and should be called **apparent thermal conductivity**. For details, refer to ASTM *Standards* C168, C177, C335, C518, C976, and C1045.

Reflective insulation impedes radiant heat transfer because the surfaces have high reflectance and low emittance values, thus reducing radiative heat transfer. (Tables 1 and 2 in Chapter 25 give typical design values.) Multiple layers of reflective materials and smooth and parallel sealed air spaces increase overall thermal resistance. Air exchange and movement must be inhibited, however.

Mass-type insulation can be combined with reflective surfaces and air spaces to obtain a higher thermal resistance. However, each design must be evaluated because maximum thermal performance of these systems depends on factors such as condition of the insulation, shape and form of the construction, means to avoid air leakage and movement, and condition of the installed reflective surfaces and their aging characteristics.

Design values of apparent thermal conductivity, thermal conductance, and thermal resistance for most common insulation materials are listed in Table 4 of Chapter 25. These values have been selected as typical and useful for engineering calculations. Test results of an insulation under appropriate conditions can give values for a particular insulation.

An insulation's form and physical structure, environment, and application conditions can affect its apparent thermal conductivity.



Fig. 5 Apparent Thermal Conductivity Versus Density of Several Thermal Insulations Used as Building Insulations



Fig. 6 Typical Variation of Apparent Thermal Conductivity with Fiber Diameter and Density

Form and physical structure vary with the basic material and manufacturing process. Typical variations include density, cell size, diameter and arrangement of fibers or particles, degree and extent of bonding materials, transparency to thermal radiation, and type and pressure of gas within the insulation.

Figure 5 illustrates the variation with density of the apparent thermal conductivity at one mean temperature for a number of insulation materials used in building envelopes. For most mass-type insulation, there is a minimum that depends on the type and form of the material, temperature, and direction of heat flow. For fibrous materials, the



Fig. 7 Typical Variation of Apparent Thermal Conductivity with Mean Temperature and Density for Fibrous Insulations

values of density at which the minimum occurs increase as both the fiber diameter or cell size and the mean temperature increase. These effects are shown in Figures 6 (Lotz 1969) and 7.

Other structural factors that affect thermal performance include compaction and settling of insulation, air permeability, type and amount of binder used, additives that may influence the bond or contact between fibers or particles, and the type and form of radiation transfer inhibitor, if used. In cellular materials, most factors that influence strength also control thermal conductivity: size, shape, and orientation of the cells; thickness of the cell walls; and gas contained in the cells. However, the radiation characteristics of cell surfaces also influence the effective conductivity.

A change in density caused by the degree of compaction of insulation powders affects their apparent thermal conductivity. Insulating concretes made from lightweight aggregates can be produced in a wide range of densities, with corresponding thermal conductivity. Fibrous insulation reaches a minimum conductivity when fibers are uniformly spaced and perpendicular to the direction of heat flow. Generally, a decrease in fiber diameter lowers conductivity for the same density (Figure 7). For cellular insulation, a specific combination of cell size, density, and gas composition produces optimum thermal conductivity.

At temperatures below 200 to 300°C, a large portion of heat transfer occurs by conduction through the air or other gas in the insulation (Lander 1955; Rowley et al. 1952; Simons 1955; Verschoor and Greebler 1952). The overall heat transfer can be closely approximated by supposition of gas conduction with all other mechanisms, each determined separately. If the gas within the insulation is replaced by another gas with a different thermal conductivity, the apparent thermal conductivity changes by an amount approximately equal to the difference in conductivity of the two gases. For example, replacing air with a fluorinated hydrocarbon (HFC) can lower the apparent thermal conductivity of an insulation by as much as 50%.

Fluorocarbon-expanded cellular plastic foams with a high proportion (greater than 90%) of closed cells retain the fluorocarbon for extended periods of time. Newly produced, they have apparent thermal conductivities of approximately $0.016 \text{ W/(m} \cdot \text{K})$ at 24°C , but this value increases with time as air diffuses into the cells and the fluorocarbon gas gradually dissolves in the polymer or diffuses out. Diffusion rates and increase in apparent thermal conductivity depend on several factors, including permeance of the cell walls to the gases involved, age of the foam, temperature, geometry of the insulation (thickness), and integrity of the surface protection provided. Brandreth (1986) and Tye (1988) showed that aging of polyurethane and polyisocyanurate is reasonably well understood analytically and confirmed experimentally. The dominant parameters for minimum aging are as follows:

- Closed-cell content >90%, preferably >95%
- Small, uniform cell diameter <<1 mm, with a larger proportion of polymer in the windows between the cells
- Small anisotropy in cell structure
- High density
- Increased thickness
- · High initial pressure of fluorocarbon blowing agent in the cell
- · Polymer highly resistant to gas diffusion and solubility
- · Polymer distributed evenly in struts and windows of cells
- Low aging temperature

Aging is further reduced, particularly for laminated and sprayapplied products, with higher-density polymer skins, or by welladhered facings and coverings with low gas and moisture permeance. An oxygen diffusion rate of less than $3.5 \text{ mm}^3/(\text{m}^2 \cdot \text{day})$ for 25 µm thickness of barrier is one criterion used by some industry organizations for manufacturers of laminated products. The adhesion of any facing must be continuous, and every effort must be made during manufacturing to eliminate or minimize the shear plane layer at the foam/substrate interface (Ostrogorsky and Glicksman 1986). Before 1987, chlorinated fluorocarbons were commonly used as cell gas. Because of their high ozone-depleting potential, chlorofluorocarbons (CFCs) were phased out during the 1990s in accordance with the Montreal Protocol of 1987. Alternatives used today are CO₂, N-pentane, and C-pentane.

Closed-cell phenolic-type materials and products, which are blown with similar gases, age differently and much more slowly.

For homogeneous, dense materials, the primary mode of heat transfer is conduction. However, as temperatures increase, heat transfer by radiation (and possibly convection) becomes a greater part of the total. The magnitude of radiation and convection depends on temperature difference, direction of heat flow, nature of the materials involved, and geometry. Because of radiation heat transfer in low-density insulation, measured apparent thermal conductivity depends on test thickness. That thickness effect increases the apparent thermal conductivity measured at installed thickness over that commonly determined at 25 mm (Pelanne 1979). From a thermal resistance standpoint, the effect is small, typically less than 10%, even for thin (e.g., 25 mm thick), low-density (e.g., 5.5 kg/m³) insulation. The effect becomes negligible for typical building applications (e.g., 150 mm insulation with a density of 11 kg/m³).

Environment and application conditions include mean temperature, temperature gradient, moisture content, air infiltration, orientation, and direction of heat flow. The magnitude of effect each has on apparent thermal conductivity varies according to the insulation material and form.

The apparent thermal conductivity of insulating materials generally increases with increasing temperature. The rate of change varies with the type and density of material. Figure 8 shows typical variations with mean temperature. However, some materials, such as fluorocarbon-expanded, closed-cell urethanes, have an inflection in the curve where the fluorocarbon changes phase from gas to liquid (see Table 10 in Chapter 25). The apparent thermal conductivity of a sample at one mean temperature (average of the two surface temperatures) only applies to the material at the particular thickness tested. Further testing is required to obtain values suitable for all thicknesses.

Insulating materials that permit a large percentage of heat transfer by radiation, such as low-density fibrous and cellular products, show the greatest change in apparent thermal conductivity with temperature and surrounding surface emittance. The effect of temperature on structural integrity is ordinarily not important for most insulation materials in low-temperature applications. In any case, decomposition, excessive linear shrinkage, softening, or other effects limit the maximum temperature for which a material is suited. At extreme temperatures, both high and low, selecting suitable materials is more difficult and must be





based on experience and performance data (see Tables 4 and 10 in Chapter 25).

Convection and air infiltration in or through some insulation systems may increase heat transfer across them. Low-density, loose-fill, large open-cell, and fibrous insulation, and poorly designed or installed reflective systems are the most susceptible. The temperature difference across the insulation and the height and width of the insulated space influence the amount of convection. In some cases, natural convection may be inherent to the system (Wilkes and Childs 1992; Wilkes and Rucker 1983), but in many cases it is a consequence of careless design and/or careless construction of the insulated structure (Donnelly et al. 1976). Gaps between board- and batt-type insulations lower their effectiveness. Board-type insulation may not be perfectly square, may be installed improperly, and may be applied to uneven surfaces. A 4% void area around batt insulation can produce a 50% loss in effective thermal resistance for ceiling application with $R = 3.4 \text{ (m}^2 \cdot \text{K})/\text{W}$ (Verschoor 1977). Similar results have been obtained for wall configurations (Brown et al. 1993; Hedlin 1985; Lecompte 1989; Lewis 1979; Rasmussen et al. 1993; Tye et al. 1981). As a solution, preformed joints in board-type insulation allow to fit the boards together without air gaps. Boards and batts can be installed in two layers, with joints between layers offset and staggered. Further details are given in Chapter 24.

The apparent thermal conductivity of insulation materials increases with moisture content. If moisture condenses in the insulation, it not only reduces thermal resistance, but may also physically damage the system. Reduction in thermal resistance depends on the material, moisture content, and moisture distribution. Section A3 of the *CIBSE Guide* (1986) covers the thermal properties of building structures affected by moisture.

Apparent thermal conductivity for insulation materials and systems is obtained by standard methods listed in Thermal Insulation and Environmental Acoustics of the *Annual Book of ASTM Standards*. The methods apply mainly to laboratory measurements on dried or conditioned samples at specific mean temperatures and temperature gradient conditions. Although the fundamental heat transmission characteristics of a material or system can be determined accurately, actual performance in a structure may vary from that indicated in the laboratory. Only field measurements could clarify the differences. Field test procedures continue to be developed. Envelope design, construction, and material may all affect the procedure to be followed. These factors are detailed in ASTM *Special Technical Publications* (STPs) 544, 660, 718, 789, 879, 885, 922, 1030, and 1116.

Mechanical Properties

Some insulation is used occasionally to support load-bearing roofs and floors, form self-supporting partitions, or stiffen structural panels. For such applications, the material's strength in compression, tension, shear, impact, flexure, and resistance to vibration may be important. These mechanical properties vary with basic composition of the insulation, density, cell size, fiber diameter and orientation, type and amount of binder (if any), and temperature and environmental conditioning.

Health and Safety

Many thermal insulation materials have good resistance to fire, vermin, rot, objectionable odors, and vapors. Some are a potential risk to health and safety, presenting either (1) risk related to storage, handling, and installation or (2) risk that occurs after installation (e.g., aging, fire, or physical disturbance). Potential hazards during manufacture are not considered here. Correct handling, installation, and precautionary measures may reduce or eliminate risks.

Combustion of insulation materials and accessories may release heat, hazardous gases, fibers, and particulates. Manufacturers' recommendations and applicable government codes and standards (ASTM *Standard* C930) give more details.

Acoustics

Some thermal insulation with open, porous surfaces is used as sound absorption material, regardless of whether thermal performance is a design requirement. Thermal insulation with high density and resilient characteristics can act as vibration insulators, either alone or in combination with other materials. Some flexible and semirigid, formed-in-place fibrous materials and rigid fibrous insulation help reduce sound transmission when placed in a composite construction.

Sound-absorbing insulation is normally installed on interior surfaces or used as interior surfacing materials. Rigid sound-absorbing insulation is fabricated into tiles or blocks, edge-treated to facilitate mechanical or adhesive application, and prefinished during manufacture. Insulation units can have a natural porous surface or mechanical perforations to facilitate the entry of sound waves; others use a diaphragm or decorative film surfacing attached only to the edges of the units, which allows the sound waves to reach the fibrous backing by diaphragm action.

Flexible, semirigid, and formed-in-place fibrous materials used for sound absorption are available in a variety of thickness and densities that determine their sound absorption characteristics.

When density is increased by reducing thickness of the material, sound absorption is generally reduced; however, as thickness increases, the influence of density decreases. A wall of staggered-stud construction, finished with airtight gypsum board, that uses resilient clips or channels on one side of the stud reduces sound transmission. Another option for reduced sound transmission is resilient insulation boards of special manufacture to prevent acoustic coupling between surfaces. A sound absorption thermal insulation blanket in a wall cavity also reduces sound transmission, depending on the type of construction.

In floors, resilient channels or separate airtight finished floor and ceiling joists form a discontinuous construction. Sound-absorbing thermal insulation placed within this construction reduces sound transmission. Sound-deadening boards underlying finish flooring absorb impact sounds and reduce airborne and impact sound transmission.

Thermal insulation boards can be placed under mechanical equipment to isolate vibration. The imposed loading and natural resonant frequency of these materials are critical for proper design. Because material must deflect properly under load to provide isolation, the system should be neither over- nor underloaded.

For further information on sound and vibration control, refer to Chapter 47 of the 2003 ASHRAE Handbook—HVAC Applications.

Other Properties

Other properties of insulating materials that can be important, depending on the application, include density, resilience, resistance to settling, air and vapor permeance, reuse or salvage value, ease of handling, dimensional uniformity and stability, resistance to chemical action and chemical change, resistance to moisture penetration, ease in fabrication, application of finishes, and sizes and thickness obtainable.

WATER VAPOR AND AIRFLOW RETARDERS

Water vapor and airflow retarders restrict the movement of water vapor and air. Although their functions are different, a single component may serve both purposes. The designer should assess needs for vapor and air movement control in the building envelope and provide a system that guarantees the required vapor and airflow retarder properties.

AIRFLOW RETARDERS

In addition to a vapor retarder, control of airflow requires an effective airflow retarder (also called an *air barrier* or *air infiltration barrier*). Although a flow of dry air may accelerate drying of a wet building component (Karagiozis and Salonvaara 1999a, 1999b), without effective control of airflow, vapor retarders are completely ineffective.

A retarder may control both vapor and airflow (i.e., act as an air/ vapor retarder). In the past, many designs were based on this idea, and measures were taken to ensure that the vapor retarder was continuous to control airflow. This remains a valid approach. Some recent designs treat airflow and vapor retarders as separate entities, but an airflow retarder should not be where it can cause moisture to condense if it also has vapor-retarding properties. For example, an airflow retarder placed on the cold side of a building envelope may cause condensation, particularly if the vapor retarder at the inside is ineffective. Instead, a carefully installed, sealed cold-side air/vapor retarder that has sufficient thermal resistance may lower the potential for condensation by raising the temperature at its indoor surface during the cold season (Ojanen and Kumaran 1996).

Air leakage characteristics can be determined with the ASTM *Standard* E1186 test method for airflow retarders placed on the interior side of the building envelope, and described according to ASTM *Standard* E1677. Specific air leakage criteria for airflow retarders in cold heating climates can be found in Di Lenardo et al. (1995). These specifications call for maximum permissible air

leakage rates between 0.05 and 0.2 L/s per square metre (as measured with an air pressure difference of 75 Pa), depending on the water vapor permeance of the outermost layer of the building envelope. The highest permissible air leakage rate applies if the permeance of the outermost layer is greater than 600 ng/(s·m²·Pa), and the lowest rate applies if the permeance is less than 60 ng/(s·m²·Pa). Intermediate values are provided, as well. The recommendations apply only to heating climates.

The effectiveness of an airflow retarder can be greatly reduced if openings, even small ones, exist in it. These openings can be caused by poor design, poor workmanship during application, insufficient coating thickness, improper caulking and flashing, uncompensated thermal expansion, mechanical forces, aging, and other forms of degradation. Faults or leaks typically occur at electrical boxes, plumbing penetrations, telephone and television wiring, and other unsealed openings in the structure. A ceiling airflow retarder should be continuous at chases for plumbing, ducts, flues, and electrical wiring. In flat roofing, mechanical fasteners are sometimes used to adhere the system to the deck, and often penetrate the airflow retarder. In heating climates, the resulting holes may allow air exfiltration and accompanying water vapor leakage into the roof.

Because an airflow retarder resists airflow, it must withstand pressures exerted by chimney (stack) effects, wind effects, or both, during construction and over the life of the building. The magnitude of the pressure may vary, depending on the type of building and sequence of construction. At one extreme, single-family dwellings may be built with the exterior cladding partly or entirely installed and insulation in place before the airflow retarder is added. Chimney effects in such buildings are small, even in cold weather, so stresses on the airflow retarder during construction are small. At the other extreme, in tall buildings, wind and chimney-effect forces are much greater. A fragile, unprotected sheet material should not be used as an airflow or vapor retarder because it will probably be torn by the wind before construction is completed.

In summary, an airflow retarder must

- Meet air permeability requirements.
- Be continuous (i.e., tight joints in the airflow retarder must be constructible; effective bonds in the airflow retarder must be made at intersections such as wall and roof).
- Accommodate dimensional changes caused by temperature or shrinkage without damage to joints or retarder material.
- Be strong enough to support the stresses applied to it. It must not be ruptured or excessively deformed by wind and stack effect. Where an adhesive is used to complete a joint, it must be designed to withstand forces that might gradually peel it away. Where the airflow retarder is not sufficiently strong to withstand anticipated wind and other loads, it must be supported on both sides to account for positive and negative wind gust pressures.

In addition, the following properties may be important, depending on the application:

- Elasticity
- Thermal stability
- · Fire and flammability resistance
- · Inertness to deteriorating elements
- Ease of fabrication, application, and joint sealing

Note that a small penetration across an airflow retarder may seriously affect its performance by concentrating air/vapor flow to allow large local deposits of water and ice. As mentioned, calculations of vapor flow, interstitial condensation, and related moisture accumulation using water vapor resistances only are useless when airflow is involved. More information on air leakage in buildings may be found in Chapter 27, Ventilation and Infiltration.

VAPOR RETARDERS

Functions and Properties

A vapor retarder slows the rate of water vapor diffusion, but does not totally prevent it. Requirements for vapor retarders in building components are not extremely stringent, because conditions on the inside and outside of buildings vary continually, air movement and ventilation can provide wetting as well as drying at various times, and water vapor entering one side of a building component can be stored and released at a later time.

If conditions are conducive to condensation, water vapor retarders help (1) keep insulation dry; (2) prevent structural damage by rot, corrosion, or expansion of freezing water; and (3) reduce paint problems on exterior wall construction (ASTM *Standard* C755).

In addition to vapor permeance, the following properties of vapor retarders are important, depending on the application:

- · Mechanical strength in tension, shear, impact, and flexure
- Adhesion
- Elasticity
- · Thermal stability
- · Fire and flammability resistance
- Resistance to other deteriorating elements (e.g., chemicals, UV radiation)
- · Ease of fabrication, application, and joint sealing

The vapor retarder's effectiveness depends on its vapor permeance, installation, and location within the insulated section. It is usually located at or near the surface exposed to the higher water vapor pressure and higher temperature. For residences with heating systems, this is usually the winter-warm side. For information on vapor barrier application, see Chapter 24.

Vapor-retarder material is usually a thin sheet or coating. However, a construction of several materials, some perhaps of substantial thickness, can also constitute a vapor retarder system. In fact, designers have many options. For example, the conditions for control of airflow and moisture movement might be achieved using an interior finish, such as drywall, to provide strength and stiffness, along with a low-permeability coating, such as a vapor retarding paint, to provide the required low level of permeance. Other designs may use more than one component. However, (1) any component that qualifies as a vapor retarder usually also impedes airflow, and is thus subject to pressure differences that it must resist; and (2) any component that impedes airflow may also retard vapor movement and promote condensation or frost formation.

Several studies have reported a significant increase in apparent permeance as a result of small holes in the vapor retarder. For example, Seiffert (1970) reports a 100-fold increase in the vapor permeance of aluminum foil when it is 0.014% perforated, and a 4000-fold increase when 0.22% of the surface is perforated. In general, penetrations particularly degrade a vapor retarder's effectiveness if it has a very low permeance (e.g., polyethylene or aluminum foil). In addition, perforations may lead to air leakage, which further erodes effectiveness.

Recently, "smart" vapor retarders have been developed that allow substantial summer drying while functioning as effective vapor retarders during the cold season. One type of smart vapor retarder has a low permeance to vapor, but is permeable to liquid water, allowing condensed moisture to dry. Korsgaard and Pedersen (1989, 1992) describe such a vapor retarder composed of a synthetic fabric sandwiched between staggered strips of plastic film. The fabric wicks free water from the building envelope, while the plastic film retards vapor flow into it.

Another type of smart vapor retarder provides low vapor permeance at low relative humidities, but much higher permeance at high relative humidity. During the heating season, indoor humidity usually is below 50% and the smart vapor retarder's permeance is low. In the summer, and on winter days with high solar heat gains, when the temperature gradient is inward, moisture moving from the exterior of the wall or roof raises the relative humidity at the vapor retarder. This leads to a higher vapor permeance and the potential for the wall or roof to dry out. One such vapor retarder is described by Kuenzel (1999). Below 50% rh, the film's permeance is less than 60 ng/(s·m²·Pa), but it increases above 60% rh, reaching 2070 ng/(s·m²·Pa) at 90% rh.

Water vapor permeances and permeabilities of some vapor retarders and other building materials are given in Table 9 in Chapter 25. Additional information on control of moisture and airflow using vapor and airflow retarders may be found in Construction Specifications Canada (1990) and Kumaran (1996).

Classifications

Historically, a material or system having a permeance of 60 ng/($s \cdot m^2 \cdot Pa$) or less qualified as a vapor retarder. More recent, refinements include the Canadian General Standards Board's (CGSB) specifications of Type I vapor retarders as having a permeance of 15 ng/ ($s \cdot m^2 \cdot Pa$) or less, and Type II as having a permeance of 45 ng/ ($s \cdot m^2 \cdot Pa$) or less before aging and 60 ng/($s \cdot m^2 \cdot Pa$) or less after aging.

Water vapor retarders are classified as rigid, flexible, or coating materials. **Rigid retarders** include reinforced plastics, aluminum, and stainless steel. These usually are mechanically fastened in place and are vapor-sealed at the joints.

Flexible retarders include metal foils, laminated foil and treated papers, coated felts and papers, and plastic films or sheets. They are supplied in roll form or as an integral part of a building material (e.g., insulation). Accessory materials are required for sealing joints.

Coating retarders may be semifluid or mastic; paint (arbitrarily called *surface coatings*); or hot melt, including thermofusible sheet materials. Their basic composition may be asphaltic, resinous, or polymeric, with or without pigments and solvents, as required to meet design conditions. They can be applied by spray, brush, trowel, roller, dip or mop, or in sheet form, depending on the type of coating and surface to which it is applied. Potentially, each of these materials is an airflow retarder; however, to meet airflow retarder specifications, it must satisfy the requirements for strength, continuity, and air permeance.

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