10

Design Tools

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Introduction

TO PREVENT POTENTIAL MOISTURE PROBLEMS IN housing in cold climates, various rules of thumb were developed during the 1930s and 40s. In principle they all stated that a "vapor barrier" should be incorporated into exterior walls on the inside (warm in winter side) of the insulation [1]. These rules were later refined to include a statement that the exterior of the wall should have a water vapor permeance five times greater than the interior vapor barrier [2]. Further refinements attempted to include rules for warm and humid climates [3]. By and large, these rules were useful, although they did not cover moisture transport mechanisms other than vapor diffusion which, it was found later, is not the greatest source of moisture transport into and through building envelopes. While these simple rules may be appropriate for extreme cold or extreme warm climates, they ignore the fact that in many locations design rules targeted at one season (summer or winter) may not be appropriate for conditions during the rest of the year.

To account for diffusion mechanisms more effectively, manual, steady-state methods were developed to determine moisture movement in walls and roofs. Being steady-state, based on a single set of assumptions, such as indoor and outdoor temperatures and relative humidities; such methods are of limited value, although their application is a significant improvement over the simple adoption of the rules of thumb previously used. These methods, known as manual design tools, all have severe limitations, and the results are difficult to interpret. However, these methods are widely used by design professionals and have traditionally been used to formulate building code requirements for vapor retarders. The proper use and limitations of these methods are discussed in the first section of this chapter, Manual Design Tools.

In an effort to provide a better understanding of the various mechanisms and interactions of moisture and heat transfer in building envelopes, transient mathematical models were developed. First thought of as strictlyresearch tools, they soon began to be useful tools for designers. In their most simple form, they applied hourly weather data to model moisture diffusion through multilayer envelope sections. In their most sophisticated form they account not only for diffusion, but also for air movement and rainwater wetting of the exterior surface and rainwater leakage.

Today, the designer has several levels of design tools available: Manual, steady-state methods, and transient (nonsteady-state) mathematical models. Manual, steady-state methods are of particular value only when comparing two or more similar designs for their relative propensity to condensation under specific environmental conditions.

Mathematical models are useful tools for a much broader set of design issues, but they too have limitations. It is precisely the sophistication of the models that impose difficulties: The input data required is often difficult to come by in the design stage, but criteria for indoor and outdoor conditions to be used for building design have been developed by ASHRAE Standard Committee 160 [3]. Another difficulty is incorporating air leakage into the design analysis. Including air leakage into the calculations requires an estimate of the air leakage rate through the wall. Although laboratory tests can be performed to give some idea of the leakage rate, the air pressure regimes even in the laboratory will not be the ones experienced in the field. However, when in-service data regarding air leakage rates of similar walls are available, the mathematical models, especially those including air leakages, are very powerful tools.

Overall, despite the lack of exact input data, the use of design tools, including models, is much superior to the simple following of rules of thumbs, and a moisture analysis should be standard procedure for any building envelope design. Exceptions can only be made for buildings in the same climate, similar occupancy, and similar envelope construction. This chapter provides guidance in the use of steady-state, manual methods, and an introduction to mathematical models. A more detailed discussion of mathematical models and modeling is provided in *ASTM MNL40, Moisture Analysis and Condensation Control in Building Envelopes.* Models are still under development and the user is encouraged to consult the various references before starting the use of models.

Manual Design Tools

The three best-known manual design tools for evaluating the probability of condensation within exterior envelopes (exterior walls, roofs, floors, or ceilings) are the dew point method, the Glaser diagram, and the Kieper diagram. All three methods compare vapor pressures within the envelope, as calculated by simple vapor diffusion equations, with saturation pressures, which are based on temperatures within the envelope. If the calculated vapor pressure is above the saturation pressure at any point within the envelope,

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TABLE 1—Example of a wall with approximate thermal and vapor diffusion properties.

Air Film or Material	Thermal Resistance (h·ft²·°F/Btu)	Thermal Resistance (m²·K/W)	Water Vapor Permeance[a] (perm)	Water Vapor Diffusion Resistance (1/perm)	Water Vapor Diffusion Resistance (10^9 m/s)
Air film (still)	0.68	0.12	160[b]	0.0063	0.11
Gypsum board, painted	0.45	0.08	5	0.2	3.5
Vapor retarder			0.06	16.67	290
Insulation	11	1.9	30	0.033	0.6
Plywood sheathing	0.62	0.11	0.5	2	35
Wood siding[c]	1	0.18	35	0.029	0.5
Air film (wind)	0.17	0.03	1000[b]	0.001	0.02
Total	13.92	2.42		18.94[d]	329.7[d]
				2.27[e]	39.73[e]

[a]1 perm=1 grain/ft²·h·in. Hg.
[b]Approximate values; permeance of surface air films is very large compared to that of other materials and does not affect results of calculations.
[c]Approximate values; permeance reflects limits ventilation of back of siding.
[d]Total diffusion resistance of wall with vapor retarder.
[e]Total diffusion resistance of wall without vapor retarder.

condensation is indicated. The dew point method used in North America, and the Glaser diagram commonly used in Europe and elsewhere, are almost identical. They differ slightly in the formulation of the vapor diffusion equation for flow through a building material and in definition of terms; the main difference lies in the graphical procedures. These methods are often misused, especially when condensation is present. Like the dew point method and Glaser diagram, the Kieper diagram is based entirely on vapor diffusion theory.

Some people advocate abandoning these design tools because of their severe limitations. Perhaps the greatest limitation is that their focus is restricted to prevention of sustained surface condensation. Many building failures, such as mold and mildew, buckling of siding, or paint failure, are not necessarily related to surface condensation. Conversely, limited condensation can often be tolerated, depending on the materials involved, temperature conditions, and the speed at which the material dries out. Another weakness is that these methods exclude all moisture transfer mechanisms other than vapor diffusion and neglect moisture storage in the building materials. This severely limits the accuracy of the calculations, especially in the case of wet materials. There are no widely accepted criteria for using manual design methods. Recommendations for use and interpretation provided in this chapter are therefore primarily based on the opinions of the author.

Dew Point Method

The dew point method [4] is based on the following diffusion equation and definitions

$$w = \delta \Delta p / d \quad (1)$$

where:

w = vapor flow per unit of area, kg/m² • s (grain/ft² • h),
$\check{u}$ = water vapor permeability, kg/m•s• Pa or s (perm • in.),[3]
p = vapor pressure, Pa (in. Hg), and
d = thickness of the material (distance along flow path), m (in.).

This equation is based on Ficks law, which uses concentration gradient as the driving potential, rather than vapor pressure. However, the concentration of water vapor in air is very low, and therefore the ideal gas law can be assumed to apply. This allows us to substitute water vapor pressure for water vapor concentration.

Water vapor permeability of a material is the permeance of 1 in. (United States) or 1 m of that material. The permeance of a sheet of material is assumed to be inversely proportional to its thickness; e.g., the permeance of 0.5-in. gypsum board is twice that of 1 -in. gypsum board.

Water vapor diffusion resistance, Z, is the inverse of permeance and is expressed in reps (1/perm) or m/s

$$Z = d/\mu \quad (2)$$

Thus, Eq (1) can also be written as

$$w = \Delta p / Z \quad (1a)$$

The dew point method is best explained and demonstrated with example calculations. As an example, we will use a frame wall construction with gypsum board (painted), glass fiber insulation, plywood sheathing, and wood siding (Table 1). We will assume 21.1°C (70°F), 40 %indoor relative humidity, and −6.7°C(20°F), 50 % outdoor relative humidity. The wall in the first example has a vapor retarder on the warm side of the cavity; the wall in the second example is identical except for the omission of the vapor retarder.

Example 1: Wall with Vapor Retarder

Step 1–The first step is to calculate the temperature drop across each material. The temperature drop is proportional to the R value as follows

$$\Delta T_{material} / \Delta T_{wall} = R_{material} / R_{wall} \quad (3)$$

Table 2 lists the resulting temperature drops and resulting temperatures at each surface.

Step 2–The next step is to find the saturation vapor pressures [Pa (in. Hg)] corresponding with the surface temperatures. These values can be found in Tables 6(a) and 6(b)

[3] 1 perm= 1 grain/ft²•h•in. Hg: 1 grain= 1/7000 lb; rep= 1/perm.

TABLE 2—Calculation of temperatures and saturation vapor pressures.[a]

Air Film or Material	Temperature, °C (°F) Drop	Surface	Saturation Vapor Pressure, Pa (in. Hg)
Indoor air			
		21.1 (70)	2503 (0.7392)
Surface air film	1.3 (2.4)		
		19.8(67.6)	2305 (0.6807)
Gypsum board	0.9 (1.7)		
		18.9(65.9)	2174 (0.6419)
Vapor retarder	0		
		18.9(65.9)	2174 (0.6419)
Insulation	22.0 (39.5)		
		−3.1(26.4)	473 (0.1394)[b]
Plywood sheathing	1.2 (2.2)		
		−4.3(24.2)	426 (0.1258)[b]
Wood siding	2.0 (3.6)		
		−6.3(20.6)	359 (0.1060)[b]
Surface air film	0.4 (0.6)		
		−6.7 (20)	371 (0.1096)[c]
Outdoor air			

[a]Temperature drop across the air film or material. Surface temperatures and saturation vapor pressures are taken at the interface for each set of air films or materials.
[b]Saturation vapor pressure over ice.
[c]Saturation vapor pressure over water. Dewpoint temperature or RH, reported in weather data, usually relates to saturation over water, not over ice.

TABLE 3—Calculation of vapor pressures in wall with vapor retarder.[a]

Air Film or Material	Saturation Vapor Pressure, Pa (in. Hg)	Vapor Pressure, Pa (in. Hg) Drop	Surface
Indoor air (40 % RH)[b]			
	2503 (0.7392)		1001 (0.2957)
Surface air film		0.3 (0.00008)	
	2305 (0.6807)		1001 (0.2956)
Gypsum board		8.6 (0.0025)	
	2174 (0.6419)		992 (0.2930)
Vapor retarder		717.9 (0.2120)	
	2174 (0.6419)		274 (0.0810)
Insulation		1.4 (0.0004)	
	472 (0.1394)		273 (0.0806)
Plywood sheathing		86.2 (0.0254)	
	426 (0.1258)		187 (0.0552)
Wood siding		1.2 (0.0004)	
	359 (0.1060)		185 (0.0548)
Surface air film		0.04 (0.00001)	
	371 (0.1096)		185 (0.0548)
Outdoor air (50 % RH)			

[a]Vapor pressures are taken at the interface for each set of air films or materials.
[b]RH is relative humidity.

or in psychrometric tables or charts (e.g., Ref. [4], Chapter 6). Table 2 lists the saturation vapor pressures for this example.

Step 3–Vapor pressure drops across each material can be calculated in much the same way as are temperature drops

$$\Delta p_{material}/\Delta p_{wall} = Z_{material}/Z_{wall} \quad (4)$$

where p is the vapor pressure [Pa (in. Hg)] and Z the vapor diffusion resistance [m/s (1/perm)]. In the example, the total resistance of the wall with the vapor retarder is as follows (seeTable 1)

$$Z_{wall} = 329.73\ 10^9 \text{ m/s } (18.94 \text{ perm}^{-1})$$

The total vapor pressure drop across the wall is calculated from indoor and outdoor relative humidities and the indoor and outdoor saturation vapor pressures (see Table 2).

$$\Delta p_{wall} = p_{indoor} - p_{outdoor} = (40/100)2503 - (50/100)371$$
$$= 1001 - 185 = 816 \text{ Pa } (0.2409 \text{ in. Hg})$$

As with temperatures, the vapor pressures at the surfaces of each material can be easily determined from the vapor pressure drops. Table 3 lists the results for the example wall with vapor retarder.

Step 4–Figure 1 shows the saturation and calculated vapor pressures. It reveals that none of the vapor pressures exceeds the saturation vapor pressure, and therefore no condensation is indicated. Vapor flow is uniform throughout the wall and can be calculated easily as follows

$$w = \Delta p_{wall}/Z_{wall} \quad (5)$$

For this example, $w=816/(329.73\ 10^9)=2.5\ 10^{-9}$ kg/m^2 • s (0.013 grain/h • ft^2). This is a very small amount of water vapor flow.

Example 2: Wall Without Vapor Retarder

Example 2 uses the same wall but without the vapor retarder. The vapor retarder has a negligible effect on temperatures (as long as air movement is not considered), and temperatures and saturation vapor pressures are therefore the same as in the wall in Example 1. Skip directly to Step 3, calculation of vapor pressures.

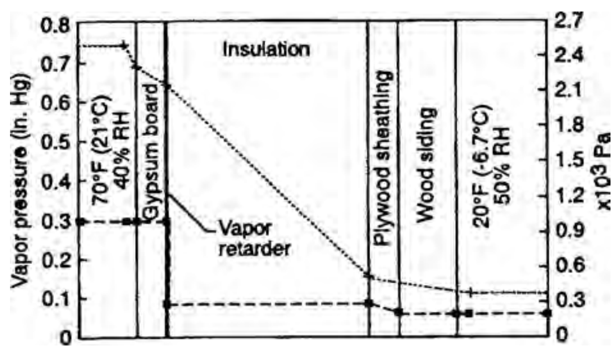

Fig. 1–Dew point method; example of a wall with vapor retarder Dotted line is saturation vapor pressure; dashed line is calculated vapor pressure.

TABLE 4—Initial and final calculation of vapor pressures in wall without vapor retarder.

Air Film or Material	Saturation Vapor Pressure, Pa (in. Hg)	Vapor Pressure, Pa (in. Hg) Drop	Vapor Pressure, Pa (in. Hg) Surface
Initial Calculation			
Indoor air (40 % RH)			
	2503 (0.7392)		1001 (0.2957)
Surface air film		2.2 (0.0007)	
	2305 (0.6807)		999 (0.2950)
Gypsum board		71.9 (0.0212)	
	2174 (0.6419)		927 (0.2738)
Insulation		12.0 (0.0036)	
	472 (0.1394)		915 (0.2702)
Plywood sheathing		718.9 (0.2123)	
	426 (0.1258)		196 (0.0579)
Wood siding		10.3 (0.0030)	
	359 (0.1060)		186 (0.0549)
Surface air film		0.4 (0.0001)	
	371 (0.1096)		185 (0.0548)
Outdoor air (50 % RH)			
	Final Calculation		
Indoor air			
	2503 (0.7392)		1001 (0.2957)
Surface air film		13.8 (0.0041)	
	2305 (0.6807)		987 (0.2916)
Gypsum board		439.8 (0.1299)	
	2174 (0.6419)		547 (0.1617)
Insulation		75.4 (0.0223)	
	472 (0.1394)		472 (0.1394)
Plywood sheathing		281.7 (0.0834)	
	426 (0.1258)		190 (0.0560)
Wood siding		4.0 (0.0012)	
	359 (0.1060)		186 (0.0548)
Surface air film		0.2 (0.00005)	
	371 (0.1096)		186 (0.0548)
Outdoor air			

Step 3–The total vapor diffusion resistance of this wall is as follows (see Table 1)

$$Z_{wall} = 39.73\ 10^9 \text{ m/s } (2.27 \text{ perm}^{-1})$$

Vapor pressure drops can again be calculated with Eq (2). The initial calculations are shown in Table 4.

Step 4–Figure 2 shows the saturation and calculated vapor pressures. This time comparison with saturation pressures reveals that the calculated vapor pressure on the interior surface of the sheathing 915 Pa (0.2702 in. Hg) is well above the saturation pressure at that location 472 Pa (0.1394 in. Hg). This indicates condensation, probably on the surface of the sheathing, because condensation within the permeable insulation is unlikely. If the location of the condensation or the condensation rate are of interest, additional calculations (Steps 5 and 6) are necessary.

Step 5–Figure 2 shows that the calculated vapor pressure exceeds the saturation vapor pressure by the greatest amount at the interior surface of the plywood sheathing. This is therefore the most likely location for condensation to occur. With condensation at that surface, vapor pressure should equal saturation at that location (see Table 4).

Step 6–The change of vapor pressure on the plywood sheathing alters all other vapor pressures as well as the vapor flow through the wall. The calculation of vapor pressures is similar to that in Step 3, but the wall is now divided into two parts: one part on the interior of the condensation plane (that is, gypsum board and insulation) and the other part on the exterior (plywood sheathing and wood siding). The vapor pressure drop over the first part of the walls is

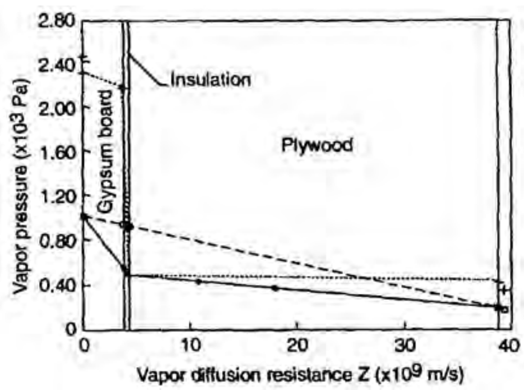

Fig. 2–Dew point method; example wall without vapor retarder. Dotted line is saturation vapor pressure; dashed line is initial calculation of vapor pressure; solid line is final calculation of vapor pressure.

$$qp_1 = 1001 - 472 = 529 \text{ Pa } (0.156 \text{ in. Hg})$$

and that over the second part is

$$qp_2 = 472 - 185 = 287 \text{ Pa } (0.085 \text{ in. Hg})$$

The vapor diffusion resistances of both parts of the wall are

$$Z_1 = (0.11 + 3.5 + 0.6)10^9 = 4.21\ \ 10^9 \text{ m/s } (0.24 \text{ perm}^{-1})$$

$$Z_2 = (35 + 0.5 + 0.02)10^9 = 35.52\ \ 10^9 \text{ m/s } (2.03 \text{ perm}^{-1})$$

The vapor pressure drops can now be calculated from

$$\Delta p_{\text{material}}/\Delta p_i = Z_{\text{material}}/Z_i \quad i = 1, 2 \tag{6}$$

Final calculations of vapor pressure are shown in Table 4. The vapor pressure no longer exceeds the saturation vapor pressure, which means that the condensation plane was chosen correctly. Figure 2 shows the vapor pressure profile (identified as vapor pressure, final calculation).

Vapor flow is no longer the same throughout the wall: vapor flow into the wall from the indoor air increased as a result of the lower vapor pressure at the plywood surface, while flow from the wall to the outside decreased. The difference between the two flows is the rate of water (solid or liquid) accumulation.

$$w'_c = \Delta p_1/Z_1 - \Delta p_2/Z_2 = 529/(4.21\ 10^9) - 287/(35.52\ 10^9)$$
$$= 118\ 10^{-9} \text{ kg/s} \cdot \text{m}^2 \ (0.61 \text{ grain/h} \cdot \text{ft}^2)$$

In our example, the plywood surface is below freezing, and this moisture would probably accumulate as frost. About a week of condensation at this rate would increase the average moisture content of the plywood by 1 %.

The limitations of this method and recommendations for its use can be found at the end of the section on manual design tools.

The dew point method can be summarized as follows:

1. Calculate temperature drops and surface temperatures.
2. Find corresponding saturation vapor pressures.
3. Calculate vapor pressure drops and vapor pressures.
4. Check if saturation pressure is above vapor pressure at all surfaces; if so, no condensation is indicated. Vapor flow through the wall may be determined if desired. (If condensation is indicated, continue with the following steps.)
5. Select condensation surface; vapor pressure at this surface equals the saturation vapor pressure.
6. Recalculate vapor pressures; if any vapor pressures are above saturation, Steps 5 and 6 should be repeated with a different condensation surface.
7. If needed, calculate rate of condensation.

Glaser Diagram

The Glaser diagram [5,6] is a variation on the dew point method. It is used primarily in Europe. The Glaser diagram is based on the following diffusion equation and definitions

$$w = -(\delta'/\mu')\Delta p/d \tag{7}$$

where:

δ' = diffusion coefficient of water vapor in air, s,
μ' = diffusion resistance factor of the material, and
d = distance along the flow path or thickness of the material, m (in.).

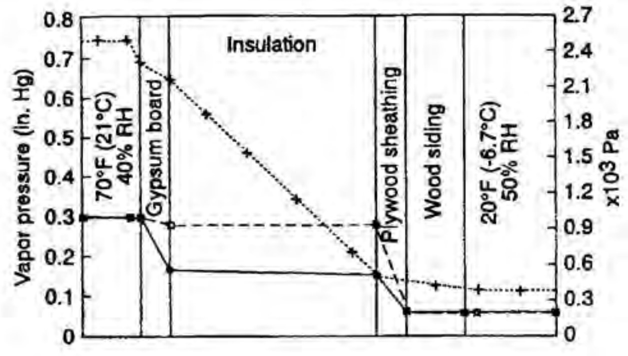

Fig. 3–Glaser diagram for example wall without vapor retarder. See caption to Fig. 2 for line designations.

The diffusion resistance factor is the ratio of the resistance to water vapor diffusion of the material and the resistance of a layer of air of equal thickness. The term *water vapor diffusion coefficient* is often used instead, defined by

$$\delta = \delta'/\mu' \tag{8}$$

Combining Eqs (7) and (8) shows that diffusion coefficient δ and permeability μ (Eq (1)) are the same. However, permeability is usually expressed in English units (perm l in.), while the diffusion coefficient is usually expressed in metric units (s). Vapor diffusion resistance is again defined as

$$Z = d/\delta$$

The only difference between the Glaser diagram and the conventional dew point method lies in the horizontal axis of the diagram. Rather than using thickness of the materials, the Glaser diagram uses the vapor diffusion resistance as the horizontal axis (Fig. 3 shows a repeat of Example 2). Thus, the materials with the largest resistance are featured most prominently. The advantage of this display is that the vapor pressure profiles are converted into straight lines. Thus, individual vapor pressures need not be calculated. In the example of the wall without vapor retarder and condensation on the plywood, the vapor pressure profile consists of two straight line segments. The saturation vapor pressure still needs to be determined from temperatures, as in the dew point method.

Kieper Diagram

The Kieper diagram was first introduced by Kieper et al. [7] and described in greater detail by TenWolde [8]. As with the dew point method and the Glaser diagram, the Kieper diagram is based entirely on vapor diffusion theory. The advantages of this method are: (a) the same diagram can be used for different wall configurations, as long as indoor and outdoor conditions are not changed, and (b) the calculation does not need to be repeated if condensation is indicated.

Rather than graphing vapor pressures and saturation pressures, the Kieper diagram uses two parameters, x and y, representing thermal properties and vapor diffusion properties of the materials in the wall, respectively. The thermal property x parameter is defined as follows:

$$x_1 = R_1/R_{\text{wall}}$$

$$x_2 = x_1 + R_2/R_{\text{wall}}$$

$$x_n = x_{n-1} + R_n/R_{\text{wall}} \quad (9)$$

where R_1 and R_2 are the R values of the individual materials and air films. Values of x range from 0 to 1. Temperature in the wall can be easily expressed as a function of x:

$$T(x) = T_i - x(T_i - T_o) \quad (10)$$

where

T_i = indoor temperature °C (°F), and
T_o = outdoor temperature °C (°F).

The vapor diffusion y parameter is defined similarly as

$$y_n = y_{n-1} = Z_n/Z_{\text{wall}} \quad (11)$$

and also ranges from 0 to 1.

If there is condensation or evaporation of liquid water at location *(x,y)* the net moisture flow to that point can be stated as

$$w_c = \frac{p_i - p_s[T(x)]}{yZ_{\text{wall}}} - \frac{p_s[T(x)] - p_o}{(1-y)Z_{\text{wall}}} = \frac{1}{Z_{\text{wall}}} \frac{p_i - p_s[T(x)] - y(p_i - p_o)}{y(1-y)} \quad (12)$$

where

w_c = moisture accumulation rate, kg/m^2•s (grain/ft^2 • h),
p_i = indoor vapor pressure, Pa (in. Hg),
p_o = outdoor vapor pressure, Pa (in. Hg),
$p_o[T(x)]$ = saturation vapor pressure, Pa (in. Hg).
Note: $T(x)$ is defined in Eq (10).

If w_c is positive, condensation (wetting) is indicated; if negative, evaporation (drying) takes place. The term w_c therefore indicates the wetting/drying potential at a given location in the wall or roof.

If we move the term Z_{wall} to the left side of Eq (12), the right side includes only *x, y,* and indoor and outdoor vapor pressures and contains no material property parameters

$$w_c Z_{\text{wall}} = \frac{p_i - p_s[T(x)] - y(p_i - p_o)}{y(1-y)} \quad (13)$$

The left term of Eq (13) has the dimension of a pressure (in. Hg or Pa). Curves in the Kieper diagram connecting points where the product $w_c Z_{\text{wall}}$ is constant represent curves of "equal wetting potential." The curve where the wetting potential is zero is often called the condensation boundary curve. These curves only change with changes in indoor or outdoor conditions and do not depend on the wall or roof construction. Figure 4 shows the Kieper diagram with the curves for 21.2 ° C (70 °F), 40 % relative humidity indoor conditions and 6.7°C (20°F), 50 % relative humidity outdoors. Various constructions can be analyzed in a single Kieper diagram if indoor and outdoor conditions are the same.

Table 5 shows the x and y values associated with the examples used previously: a frame wall with and without a vapor retarder. When the wall profiles are entered in the Kieper diagram, as shown in Fig. 5, it is obvious that the wall with the vapor retarder is entirely outside the condensation region (the area below the condensation boundary curve). As expected, the curve for the wall without the vapor retarder penetrates the condensation region in the diagram. The point on the curve that penetrates the deepest (i.e., the plywood surface) represents the greatest wetting potential. This point falls between curve *d* ($w_c Z$ = 1.0 in. Hg or 3386 Pa) and *e* ($w_c Z$ = 1.5 in. Hg or 5080 Pa). The wetting potential can be estimated by interpolation:

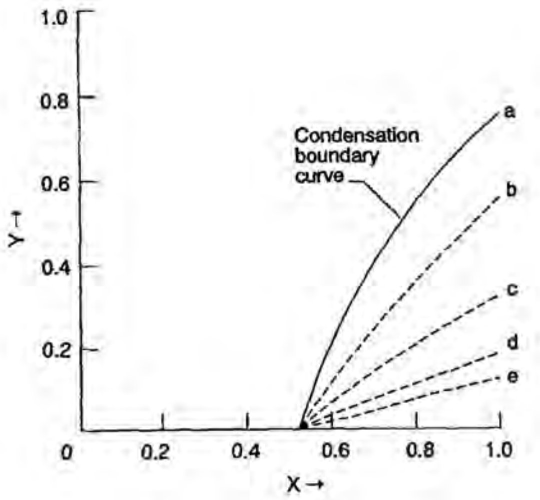

Fig. 4–Kieper diagram: moisture accumulation curves for indoor conditions of 70°F (21°C), 40 % RH and outdoor conditions of 20°F (-6.7°C) 50 % RH. The WcZ values for the curves are *(a)* 0, *(b)* 0.2 in. Hg (677 Pa), (c) 0.5 in. Hg (1693 Pa), *(d)* 1.0 in. Hg (3386 Pa), and *(e)* 1.5 in Hg (5080 Pa).

$$w_c Z = 1.4 \text{ in. Hg (4740 Pa)}$$

With Z = 2.27 perm^{-1} (39.710^9 m/s), the estimated rate of condensation is

$$w_c = 1.412.27 = 0.62 \text{ grain/h} \cdot \text{ft}^2 \ (12010^{-9} \text{ kg/m}^2 \cdot \text{s})$$

Limitations of Manual Design Tools

The methods discussed previously have the same severe limitations and should therefore be used with caution. The methods only "predict" condensation, not moisture damage. Many constructions can sustain limited periods of condensation without significant damage, especially if the temperatures are near or below freezing and the material is able to dry quickly. In addition, performance problems such as mold and mildew or paint failure are not necessarily related to surface condensation.

The methods ignore air leakage. If air leakage is present, it tends to dominate moisture transport [9]. Even small amounts of indoor air leakage into the wall (exfiltration) can more than double the condensation rate during winter [10]. However, where exfiltration increases the potential for wetting, infiltration of dry cold air decreases that potential. If the amount and direction of airflow are known, the effects may be estimated with more sophisticated methods, discussed later in this chapter. However, usually insufficient information is available on the airflow patterns in wall and roof cavities to estimate the effect on moisture conditions.

The methods do not recognize liquid capillary transport or any transport mechanisms other than diffusion. This

TABLE 5—Kieper diagram: x and y values for example wall with and without a vapor retarder.

Air Film or Material	Thermal resistance,[a] h·ft²·°F/Btu	Permeance,[b] perm.	Diffusion Resistance, rep	x	Vapor Retarder, y	No Vapor Retarder, y
Air film (still)	0.68	160	0.006	0.049	0.0003	0.003
Gypsum board, painted	0.45	5	0.2	0.081	0.011	0.091
Vapor retarder		0.06	16.67	0.081	0.891	
Insulation	11	30	0.033	0.871	0.893	0.105
Plywood sheathing	0.62	0.5	2	0.916	0.998	0.986
Wood siding	1	35	0.029	0.988	1.000	0.999
Air film (wind)	0.17	1000	0.001	1.000	1.000	1.000
Total						
With vapor retarder	13.92		18.94			
Without vapor retarder	13.92		2.27			

[a]See Table 1 for SI values.
[b]1 perm = 1 grain/ft²·h·in. Hg.

tends to result in the underprediction of moisture transfer in materials such as wood at higher moisture contents. For instance, in plywood, moisture transfer may be as much as 16 times greater under wet conditions than under dry conditions and in waferboard, three to four times greater under wet conditions [11].

All three methods are steady-state and do not recognize the effects of moisture and heat storage. This may be a major drawback when trying to determine the potential for damage in a wall or roof with large storage capacity or in a climate with a low drying potential. In those cases, moisture stored during an earlier part of the season may cause damage at a later time.

When moisture condenses or evaporates, latent heat is released or absorbed, raising or lowering temperatures. The analysis does not take this into account. In most practical cases, this is not a major effect unless the condensation/evaporation takes place on an exposed surface (for example, window condensation).

All three methods are one-dimensional; that is, the effect of corners, holes, or cracks, studs, or other thermal "bridges" are not included.

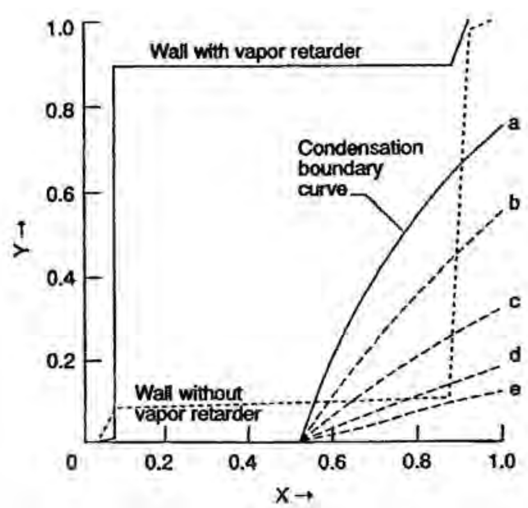

Fig. 5–Kieper diagram: example wall with and without vapor retarder, indoor conditions of 70 °F (21 °C), 40 % RH and outdoor conditions of 20°F (–6.7°C). 50 % RH. The w_CZ values for the curves are *(a)* 0, *(b)* 0.2 in. Hg (677 Pa), *(c)* 0.5 in. Hg (1693 Pa), *(d)* 1.0 in. Hg (3386 Pa), and *(e)* 1.5 in. Hg (5080 Pa).

Recommendations for Use

Although manual design tools have many limitations and are based on simplifying assumptions, they have the advantage of being relatively simple. For that reason, they will continue to be used, despite the increased availability of much more sophisticated computer programs. If steady-state tools are used, the authors suggest the following:

- Only use these methods for analyzing airtight construction and in cases where wetting by rain or heating by direct sunlight does not play a significant role.
- Only use these methods to estimate seasonal mean conditions, rather than daily or even weekly mean conditions.
- Use monthly averages for indoor and outdoor temperatures and humidities.
- Results obtained with any of these methods should be considered as approximations and be used with prudent care.

Software for Heat, Air, and Moisture (HAM) Transport

Introduction

There has been a rapid improvement in the capabilities of computer-based moisture analysis tools that can predict the movement and accumulation of moisture in building components and materials. However, there still is a large gap between needs of architects, designers, and practitioners and the heat, air, moisture computer models currently available at the marketplace.

Straube and Burnett [12] discussed HAM models available in the marketplace and suitable for the enclosure design, stating:

> "Structural, mechanical and electrical engineers use various different mathematical models to analyze the response of the modeled system or subsystem and then improve, adjust, or revise the system as needed until a final design is arrived at. The building industry is moving towards a similar situation with building enclosures. However, we in North America still have some way to go in terms of developing a professional

consensus on which models are to be preferred, what analysis procedures are cost and qualitatively effective, and how to develop the necessary experience to use these models properly. Rapidly changing technologies, e.g., materials and interior building environments, combined with higher expectations of performance for both the enclosure and the building, have created a very real need for the development and use of practical hygrothermal analysis methods."

Discussing the reasons for conducting of a hygrothermal analysis, Straube and Burnett [12] highlight the comparative power of HAM modeling:

> "Although a simple analysis technique may provide neither absolutely correct nor accurate results, so long as a satisfactory decision can be made (ie., a safe design) with this information, the technique fills the need. Consider also the situation where conducting a parametric analysis where the accuracy between results (relative results) may be much more accurate than the absolute value of any particular result."

Improvements Needed to Make Software More Useful to Designers

Zhang [13], who discussed the needs of users, stated that combined heat, air, moisture, and pollutants transport in buildings exists in different scales. These scales involve transports in the surroundings of the building, the building enclosure, different zones in the building and local environments around occupants. A system model is needed for simulating these transport processes and their impacts on indoor environmental quality. Components of this system model should include:

- amulti-zonal network flow model for whole building,
- a room model for air and pollutant movement in ventilated spaces,
- a coupled heat, air moisture, (HAM) and pollutant transport model for the building enclosure,
- an HVAC model for describing the dynamics of the heating, ventilating and air-conditioning (HVAC) system, and
- shared databases of weather conditions, transport properties of building materials, and volatile organic compounds (VOCs) emissions from building materials and furnishings.

Discussing multi-zone models Zhang [13] stated:

> "A whole building can be divided into multiple zones, each representing a space or aggregated spaces (office workstation, cubical, room, corridor, stair shaft, elevator shaft, etc.) whose environmental conditions can be represented by averaged values, and controlled through a single controller such as a thermostat or an 'airstat.'[4] Lumped parameters are defined for each zone including the pressure, temperature, relative humidity and pollutant concentrations. The primary purpose of the multizonal model is to capture the interactions among the different zones of a building, and the ambient weather conditions, and provide a system level prediction of the building performance. In addition, it should also be able to use the outputs from the other component models in order to predict the building performance more accurately."

Most of HAM models can assist in understanding of moisture response of the building enclosure, particularly in terms of amount of expected condensation in relation to the selected climatic conditions and identification of potential problems. Yet, the designer must modify the material selection and assembly composition to avoid reduction of performance that could be created by rain penetration, construction moisture or moisture carried by capillary or other forces. Current HAM models are suitable for the comparative assessment only.

To expand the use of HAM modeling from the sensitivity studies to the real time performance analysis the following is required:

- Numerical part of the HAM (Heat, Air and Moisture) transport model must be validated;
- Moisture transport characteristics[5] i.e., the moisture storage and permeability (moisture conductivity) must also be validated for each of the materials involved in the analyzed building assembly.
- Detailed information on boundary conditions must be provided, especially on the relevant air pressure differences.

Hagentoft et al. [14], describe requirements for numerical models and their validation, developed by an international group. Work of this group provided a basis for development of a European standard.

Ensuring that moisture transport properties presented in one or other handbook or database are applicable for the analyzed case is more difficult. This difficulty stems from two reasons:

1. Each HAM model uses an individually tailored set of material characteristics
2. Despite many research papers (as an example see Roels [15], Roels et al. [16,17], Carmeliet et al. [18]) and despite the existence of internationally agreed set of requirements for material characterization [19] adequate characterization of materials is not a part of all the recently published North American hygrothermal datasets.

An international group (see Bomberg et al. [19]) required that, independently of what methods are used for the determination of hygrothermal properties, each material must be adequately characterized, and recommended minimum requirements for material characterization. Grunewald et al. [20] proposed a minimal set of parameters for hygrothermal material characterization as input to simulation programs. Perhaps even more importantly, air flow often dominates the flow of moisture in cavity construction (frame construction), especially when it comes to drying of wet assemblies. Detailed information is therefore needed on the typical air flows within and between parts of the envelope, and the pressures that drive them.

ASHRAE Standard Committee 160P (Design Criteria

[4] In analogy to a "thermostat," "airstat" is introduced here as a device with a sensor and information processing algorithm (e.g., compare measured value with a "setpoint" and send our control signals to actuators such as an aircleaning or ventilating device.

[5] The term "material property" implies a physical quantity generaaly independent of the used test method, while the term "material characteristics" highlights that the quantity may vary with changes in the applied test method (see Bomberg et al. [19]).

for Moisture Control in Buildings) is currently developing a standard for hygric design loads that include hourly climatic data (also see draft of a European Standard prEN13013-3 [21]). Nevertheless, there is an urgent need for developing ASTM standards addressing:

- Requirements for validation of HAM models.
- Standard procedures for validation of hygrothermal material characteristics.
- Standard procedures for validation of hygrothermal characteristics of cladding assemblies (this would define the effect of air and moisture venting of the cladding system).

HAM Software Available in Marketplace

A survey of existing HAM models used in different places (IAE Annex 24, 1988) revealed more than 35 different HAM models, out of which at least ten are available in the United States. Instead of repeating the survey, the authors instead present only a few selected hygrothermal models.

Analytical, Simplified 1-D, Steady State Model of Heat and Moisture Transport (COND)

COND is not a simulation tool but a software program for the hygrothermal evaluation of different building envelope designs. It is not able to calculate the real temperature and moisture fields that will be present in the construction. However, similar to the Glaser methods it can provide expected values, which allow for an approximate evaluation of the building envelope. This helps to evaluate the performance of a building envelope under certain climatic conditions, including the prediction of moisture damage. The method of calculation takes into consideration condensation and redistribution of moisture. Therefore, the evaluation of building envelopes will be closer to reality than with steady-state methods based on the conventional vapor pressure profiles (Glaser, dew point, or Kieper methods).

The model works with one-dimensional and steady-state heat and moisture transport through a vapor permeable construction that consists of many layers. The climate is described by constant temperature and relative humidity on the inside and outside of the construction. The temperature difference results in heat flow through the construction and after certain period steady-state heat flow is established. The profile of the temperature associated with steady-state conditions results in a vapor flow through the construction. Here again, a steady vapor flow is reached after a certain time. The profile of the vapor pressure is also calculated. If the calculated vapor pressure exceeds the saturated vapor pressure (which is directly dependent on the temperature), condensation occurs inside the construction.

As soon as condensation water accumulates in the construction, it causes both liquid and vapor fluxes. This is an essential enhancement in comparison to the Glaser dew point scheme, which disregards capillary liquid water transport. Following the global condition of equilibrium, the inward flux of moisture is equivalent to the outward flux. These conditions of equilibrium are defined with various balance equations. The solution of the generated system of equations is the distribution of moisture in the stationary condition. Through consideration of time-dependent transient phenomena, an estimation of the expected distribution of moisture can be made, for the final effect after a considered elapse of time.

COND was developed by the Technical University of Dresden (http://www.bauklimatik-dresden.de/cond/index_en.html) but in North America can be obtained from the Syracuse University, Syracuse, NY, 13244). The use of the software is, however, limited because of lack of hygrothermal material characteristics.

1-D (pseudo 3-D), Transient Model of Heat, Air and Moisture Transport (WALLDRY)

WALLDRY is a relatively simple heat, air, and moisture transport simulation program that uses basic engineering equations to describe the transport phenomena that occur in a siding-clad, wood-framed wall.

The WALLDRY program was created for Canada Mortgage and Housing Corporation (CMHC) to evaluate the drying of wood frame residential wall assemblies clad with sidings (with or without strapping). Of specific interest were the effects of air leakage through the siding and ventilation of the air space created by the strapping. Several unique aspects of the assembly (the siding, the air space created by the strapping and the framing in the inner portion of the wall) are captured in a psuedo-3-dimensional topology. The topology is called “psuedo-3-dimensional” because the wall assembly is divided into a three-dimensional system of elements, but the physical model and numerical solution are not constructed to model transfers between all adjacent elements. Instead, one-dimensional formulations of the physical equations are applied to the elements in one plane and then another. This has permitted treatment of the wall studs as sources or sinks for moisture while airflow within the wall cavity is not addressed.

The airflow model is used to predict the hourly mean air velocity and mass flow of air at each of the nine elements that make up the air space behind the siding. These velocity and mass flow values are used as inputs for the heat flow and moisture transfer models. The airflow model assumes that flows are driven by air pressure differences related to wind pressures and stack effects. Air is introduced to an element from adjacent elements or air leakage through gaps in the siding. Similarly, air leaves an element to adjacent elements or leakage through siding gaps. The continuity of mass principle applies. The definition of joint properties allows consideration of cladding without intermediate joints. The heat and moisture transfer rates are not independent of each other; however, they are calculated independently and the results are used to repeat the calculations for a total of three passes through the heat and moisture transfer sub routines. Each pass through the subroutines makes a small correction to the calculated temperatures and moisture contents. Whereas the original program assumed constant properties for materials, the updated version incorporates moisture sensitive properties, which are adjusted in the iterative solution.

This software is now being updated in Miscrosoft Visual Basic.NET, which permitted numerous modifications to be made. Material properties will be selected from the international database (see previous section) or other sources. Hourly weather files include both laboratory conditions from experiments, as well as real weather files containing:

- Indoor temperatures and relative humidity as fixed or variable histories,
- Outdoor temperature and RH histories,
- Wind speed and direction,
- Solar radiation (on North, East, South and West wall surfaces).

Wind pressure coefficients are currently built into the program but they may be altered for specific cases. Data from field and laboratory experiments have been used to assess if predictions by the model have been adequate. These include test huts in the Atlantic provinces and Ontario, as well as chamber studies in Ottawa and Vancouver. All such comparisons were made on the original version of the software. Past comparisons were not always successful but this had as much to do with difficulties in experimentation as in specifying the material and physical boundary conditions.

The software will not be supported for commercial applications but may be provided on request for research and educational purposes by application to Silvio Plescia, Housing Standards and Technology Group, Canada Mortgage and Housing Corporation, National Office, 700 Montreal Road, Ottawa, Ontario, K1A0P7.

1-D and 2-D Transient Models of Heat and Moisture Transport (WUFI/ORNL)

Not much information can be added to the chapter in the ASTM manual [12] that describes physical background, equations, and material properties used in WUFI/ORNL software. The software is user friendly and uses an a few engineering simplifications that upon a careful verification show good overall approximations of the moisture transfer phenomena. Those approximation are perhaps less precise during transient, repeated wetting and drying iterations but precise enough for any comparative assessment of building constructions.

The simplifications used in the WUFI model are:

- Material transport properties for wetting of the wall under influence of rain are different from those under moisture redistribution in the material,
- Transport coefficients for moisture contents above the hygroscopic region are approximated with a linear in the logarithmic scale dependence of moisture content. Yet, as this approximation is used between two "characteristic" moisture contents it is therefore not without physical justification.

WUFI provides a good engineering tool for the comparative assessment of constructions. The main weakness of this software is lack of airflow calculating capabilities and the restriction to heat and moisture. The database for materials typically used in North America is limited but rapidly increasing because simple input requirements are more accessible than those more complex that are needed for research models. For the American version of WUFI, called WUFI/ORNL, the contact is the ORNL (e-mail: Karagiozisan@ornl.gov).

1-D and 2-D Transient Models of Heat, Air, and Moisture Transport (CHAMPS/DELPHIN)

In contrast with the three software programs described above, this software is not a practical engineering tool but a more powerful research tool for real time calculations. The material characteristics are much more complex, they include all information used for WUFI and more. Therefore, the determination of material characteristics requires much more effort. An engineering model of material characteristics (Grunewald et al. [20]) would permit using this software for engineering applications. This work is combined with development of the validation procedures for material characteristics.

DELPHIN has been developed by the Technical University of Dresden (http://www.bauklimatik-dresden.de) but a new version that includes air and VOC flows is currently being developed in collaboration between Syracuse University and Technical University of Dresden. This software is not likely to be supported for commercial use but will be available for the collaborating research groups.

Other HAM Software Used by Research Organizations

All leading research groups in Argentina, Belgium, Canada, Finland, Holland, Israel, Japan, Germany, and the United States have HAM models used in-house. In North America, the Oak Ridge National Laboratory and NRC Canada have 2-D models with airflow capability. These model are expanded from the Latenite (the code developed by NRCC together with VTT, Finland). Typically, these research laboratories measure material properties and use them in the appropriate model simulations. One wonders if this is not one of the reasons for such a slow progress in developing material characteristics and validation tools for HAM modeling in public domain.

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