

# Manual Analysis Tools

by Anton TenWolde<sup>1</sup>

THERE ARE TWO FUNDAMENTAL APPROACHES to design for moisture control. One approach focuses on the thermal and moisture properties of the building envelope (exterior walls, roofs, and ceilings) needed to withstand the interior and exterior conditions. The second approach attempts to adjust the indoor climate to the thermal and moisture characteristics of the building envelope. This chapter deals with design tools for the exterior envelope only. Recommendations for indoor climate control can be found elsewhere in this handbook.

The traditional tools currently available for design of the exterior building envelope all have severe limitations, and the results are difficult to interpret. However, for lack of better tools, these methods are used by design professionals and form the basis for current building codes dealing with moisture control and vapor retarders. The proper use and limitations of these methods are discussed in the first section of this chapter, Manual Design Tools. A few relatively simple numerical methods not included elsewhere are discussed briefly in the section on Numerical Tools.

## 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, 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.

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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 [1] is based on the following diffusion equation and definitions

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

where

$w$  = vapor flow per unit of area, kg/m<sup>2</sup> · s (grain/ft<sup>2</sup> · h),  
 $\mu$  = water vapor permeability, kg/m · s · Pa or s (perm · in.)<sup>2</sup>,  
 $p$  = vapor pressure, Pa (in. Hg), and  
 $d$  = flow path or thickness of the material, m (in.)

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 OS-in. gypsum board is twice that of 1-in. gypsum board.

Water vapor 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

<sup>2</sup>1 perm = 1 grain/ft<sup>2</sup> · h · in. Hg; 1 grain = 1/7000 lb; 1 rep = 1/perm.

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

Air Film or Material	Thermal Resistance		Permeance, <sup>a</sup> perm	Diffusion Resistance	
	(h · ft <sup>2</sup> · °F/Btu)	(m <sup>2</sup> · K/W)		Z = d/μ, 1/perm	Z = d/δ, 10 <sup>9</sup> m/s
Air film (still)	0.68	0.12	160 <sup>b</sup>	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 <sup>c</sup>	1	0.18	35	0.029	0.5
Air film (wind)	0.17	0.03	1000 <sup>b</sup>	0.001	0.02
Total	13.92	2.42	...	18.94 <sup>d</sup> 2.27 <sup>e</sup>	329.73 <sup>d</sup> 39.73 <sup>e</sup>

<sup>a</sup> 1 perm = 1 grain/ft<sup>2</sup> · h · in. Hg.

<sup>b</sup> Approximate values; permeance of surface air films is very large compared to that of other materials and does not affect results of calculations.

<sup>c</sup> Approximate values; permeance reflects limits ventilation of back of siding.

<sup>d</sup> Total diffusion resistance of wall with vapor retarder.

<sup>e</sup> Total diffusion resistance of wall without vapor retarder.

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

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

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 6a & 6b or in psychrometric tables or charts (e.g., Ref 1, 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

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

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 (see Table 1)

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

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).

TABLE 2—Calculation of temperatures and saturation vapor pressures.<sup>a</sup>

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

<sup>a</sup>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.

<sup>b</sup>Saturation vapor pressure over ice.

<sup>c</sup>Saturation vapor pressure over water. Dewpoint temperature or RH, reported in weather data, usually relates to saturation over water, not over ice.

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

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 con-

TABLE 3—Calculation of vapor pressures in wall with vapor retarder.<sup>a</sup>

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

<sup>a</sup>Vapor pressures are taken at the interface for each set of air films or materials.

<sup>b</sup>RH is relative humidity.

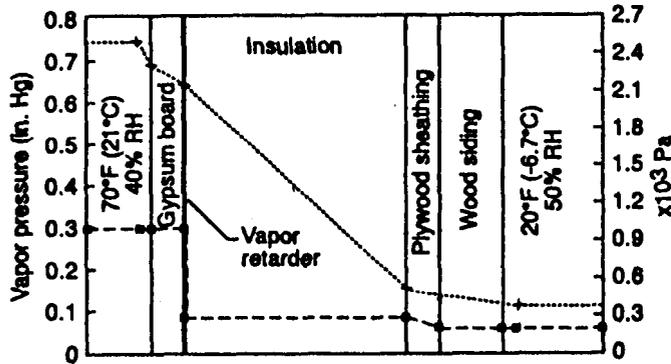


FIG. 1—Dew point method; example wall with vapor retarder. Dotted line is saturation vapor pressure; dashed line is calculated vapor pressure.

condensation is indicated. Vapor flow is uniform throughout the wall and can be calculated easily as follows

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

For this example,  $w = 816 / (329.73 \cdot 10^9) = 2.5 \cdot 10^{-9} \text{ kg/m}^2 \cdot \text{s}$  (0.013 grain/h · ft<sup>2</sup>). 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.

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

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

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

$$\Delta p_1 = 1001 - 472 = 529 \text{ Pa (0.156 in. Hg)}$$

and that over the second part is

$$\Delta p_2 = 472 - 185 = 287 \text{ Pa (0.085 in. Hg)}$$

The vapor diffusion resistances of both parts of the wall are

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

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

The vapor pressure drops can now be calculated from

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

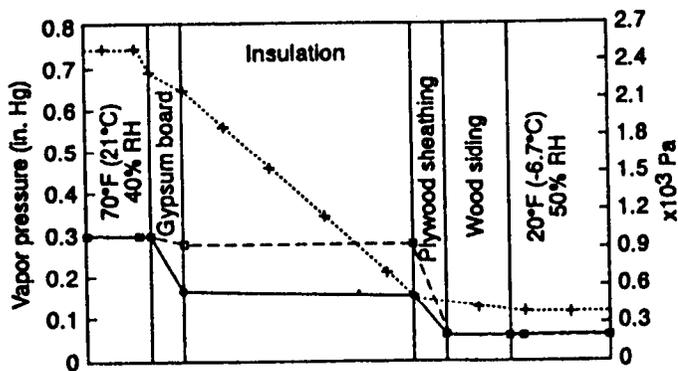


FIG. 2—Dew point method; example wall without vapor retarder. Dotted line is saturation vapor pressure; dashed line is initial calculation of vapor pressure; solid line is final calculation of vapor pressure.

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

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.

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

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 [2,3] 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

$$w = -(\delta'/\mu') \Delta p/d \quad (7)$$

where

- $\delta'$  = diffusion coefficient of water vapor in air, s,
- $\mu'$  = diffusion resistance factor of the material, and
- $d$  = flow path or thickness of the material, m (in.).

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

$$\delta = \delta'/\mu' \quad (8)$$

Substituting  $\delta$  in Eq 6 shows that diffusion coefficient  $\delta$  and permeability  $\mu$  (Eq 1) are the same. However, permeability is usually expressed in English units (perm · 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.

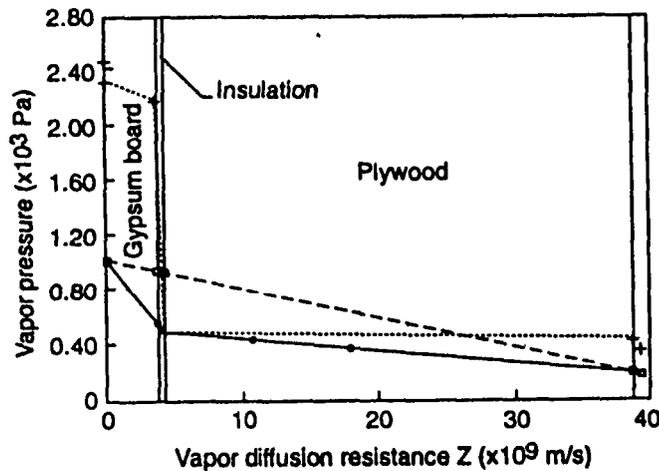


FIG. 3—Glaser diagram for example wall without vapor retarder. See caption to Fig. 2 for line designations.

### Kieper Diagram

The Kieper diagram was first introduced by Kieper et al. [4] and described in greater detail by TenWolde [5]. 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

$$\begin{aligned} x_1 &= R_1/R_{\text{wall}} \\ x_2 &= x_1 + R_2/R_{\text{wall}} \\ x_n &= x_{n-1} + R_n/R_{\text{wall}} \end{aligned} \quad (9)$$

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

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

where

- $w_c$  = moisture accumulation rate,  $\text{kg/m}^2 \cdot \text{s}$  ( $\text{grain/ft}^2 \cdot \text{h}$ ),
  - $p_i$  = indoor vapor pressure, Pa (in. Hg),
  - $p_o$  = outdoor vapor pressure, Pa (in. Hg),
  - $p_s[T(x)]$  = 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  $Z_{\text{wall}}$  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.

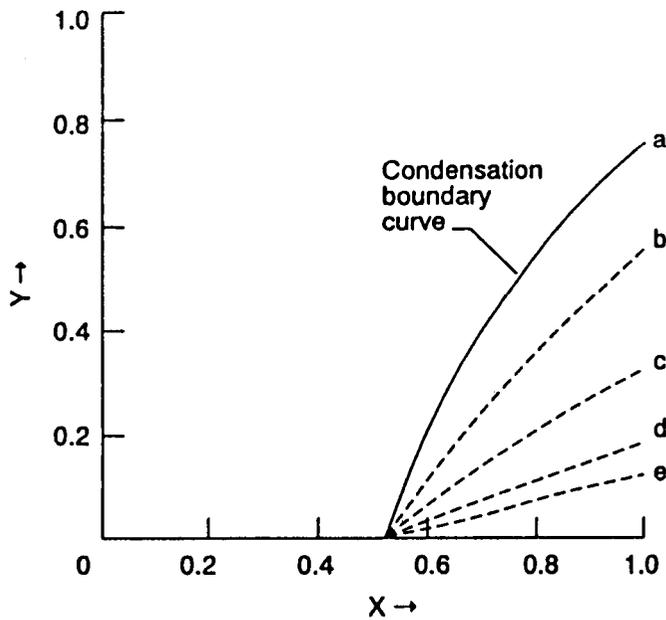


FIG. 4—Kieper diagram: moisture accumulation curves for indoor conditions of 70°F (21°C), 40% RH and outdoor conditions of 20°F (-6.7°C), 50% RH.  $w_cZ$  values for the curves are (a) 0, (b) 0.2 in. Hg (677 Pa), (c) 0.5 in. Hg (1693 Pa), (d) 1.0 in. Hg (3366 Pa), and (e) 1.5 in Hg (5060 Pa).

Hg or Pa). Curves in the Kieper diagram connecting points where the product  $w_cZ_{wall}$  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  $d$  ( $w_cZ = 1.0$  in. Hg or 3386 Pa) and  $e$  ( $w_cZ = 1.5$  in. Hg or 5080 Pa). The wetting potential can be estimated by interpolation:

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

With  $Z = 2.27 \text{ perm}^{-1}$  ( $39.7 \cdot 10^9 \text{ m/s}$ ), the estimated rate of condensation is

$$w_c = 1.4/2.27 = 0.62 \text{ grain/h} \cdot \text{ft}^2 \text{ (} 120 \cdot 10^{-9} \text{ kg/m}^2 \cdot \text{s)}$$

### 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. Even small amounts of indoor air leakage into the wall (exfiltration) can more than double the condensation rate during winter [6]. 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 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 [7].

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

Air Film or Material	Thermal resistance, <sup>a</sup> h · ft <sup>2</sup> · °F/Btu	Permeance, <sup>b</sup> 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			

<sup>a</sup> See Table 1 for SI values.

<sup>b</sup> 1 perm = 1 grain/ft<sup>2</sup> · h · in. Hg.

TABLE 6a—Saturation water vapor pressures (Pa) over water and ice, SI units.

Temperature		0	1	2	3	4	5	6	7	8	9
-30 °C to -39 °C	ice	38	34	31	28	25	22	20	18	16	14
	wtr	51	46	42	38	34	31	28	26	23	21
-20 °C to -29 °C	ice	103	94	85	77	70	63	57	52	47	42
	wtr	125	115	105	96	88	81	73	67	61	56
-10 °C to -19 °C	ice	260	238	217	198	181	165	151	137	125	114
	wtr	286	264	244	225	208	191	176	162	149	137
0 to -9 °C	ice	611	562	517	476	437	402	368	338	310	284
	wtr	611	568	528	490	455	421	391	362	335	310
0 to 9 °C	wtr	611	657	705	758	813	872	935	1001	1072	1147
10 to 19 °C	wtr	1227	1312	1402	1497	1598	1704	1817	1937	2063	2196
20 to 29 °C	wtr	2337	2486	2643	2809	2983	3167	3361	3565	3780	4006
30 to 39 °C	wtr	4243	4493	4755	5031	5320	5624	5942	6276	6626	6993
40 to 49 °C	wtr	7378	7780	8201	8642	9103	9586	10089	10616	11166	11740

note 1: for temperatures below 0°C saturation vapor pressures are listed over ice and water (wtr).

note 2: saturation vapor pressures for intermediate temperatures can be estimated by interpolation.

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.

### 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 such as MOIST. If steady-state tools are used, the author suggests 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.

### NUMERICAL TOOLS

This section briefly discusses several relatively simple numerical analytical methods that are not included in other chapters. All the models discussed in this section are limited to one-dimensional analysis.

MOISTWALL, developed at the Forest Products Laboratory, is a numerical version of the Kieper diagram [5]. The program calculates moisture accumulation potential at each material surface using Eq 12. If all values are negative, no condensation is indicated. If some results are positive, the maximum is selected. MOISTWALL was implemented on a programmable calculator and has not yet been adapted to personal computers.

TABLE 6b—Saturation water vapor pressures (in. Hg) over water and ice, English units.

Temperature		0	2	4	6	8
-10 °F to -18 °F	ice	0.02203	0.01974	0.01766	0.01579	0.01410
	wtr	0.0277	0.0250	0.02267	0.0204	0.0185
0 to -8 °F	ice	0.0376	0.0339	0.0305	0.0274	0.0246
	wtr	0.0448	0.0407	0.0370	0.0336	0.0305
0 to 8 °F	ice	0.0376	0.0418	0.0463	0.0513	0.0568
	wtr	0.0448	0.0492	0.0539	0.0591	0.0647
10 to 18 °F	ice	0.0629	0.0695	0.0767	0.0846	0.0933
	wtr	0.0708	0.0774	0.0845	0.0923	0.1006
20 to 28 °F	ice	0.1027	0.1130	0.1243	0.1366	0.1500
	wtr	0.1096	0.1193	0.1298	0.1411	0.1532
30 to 38 °F	ice	0.1645	0.1803			
	wtr	0.1663	0.1804	0.1955	0.2117	0.2290
40 to 48 °F	wtr	0.2477	0.2676	0.2890	0.3118	0.3363
50 to 58 °F	wtr	0.3624	0.3903	0.4200	0.4518	0.4856
60 to 68 °F	wtr	0.5216	0.5599	0.6007	0.6441	0.6902
70 to 78 °F	wtr	0.7392	0.7911	0.8463	0.9047	0.9667
80 to 88 °F	wtr	1.0323	1.1017	1.1752	1.2530	1.3351
90 to 98 °F	wtr	1.4219	1.5136	1.6103	1.7124	1.8200
100 to 108 °F	wtr	1.9334	2.0529	2.1786	2.3110	2.4503
110 to 118 °F	wtr	2.5968	2.7507	2.9125	3.0823	3.2606

note 1: for temperatures below 32°F saturation vapor pressures are listed over ice and water (wtr).

note 2: saturation vapor pressures for intermediate temperatures can be estimated by interpolation.

In the MOISTWALL-2 program, the effect of airflow was added to vapor diffusion [6]. The airflow is assumed to be a uniform one-dimensional exfiltrative or infiltrative flow. In all other respects, this method has the same limitations as the manual design methods. As with the original MOISTWALL program, MOISTWALL-2 has not been implemented on a personal computer and is therefore not readily available.

An analytical model of moisture in cavity walls or roofs was published by Cunningham [8,9]. This model is a simpler representation of moisture flow and storage: the cavity is treated as a single homogeneous region with the wood stud as a moisture storage medium. In a later version [10], sep-

arate moisture release into the cavity (such as leaks, soil moisture) are also included. This simpler approach is very useful for estimating approximate drying times for wet wall cavities, assuming different levels of air leakage. However, the method is less suited to estimating the response to large temperature gradients in the insulated cavity (very cold or hot climates) or to using hygroscopic insulation materials (e.g., cellulose).

A description of a one-dimensional finite-difference moisture transfer model was recently published by Spolek et al. [11]. The driving force within each material is assumed to be the moisture content gradient, whereas hygroscopic properties are considered at the surface of materials only. While

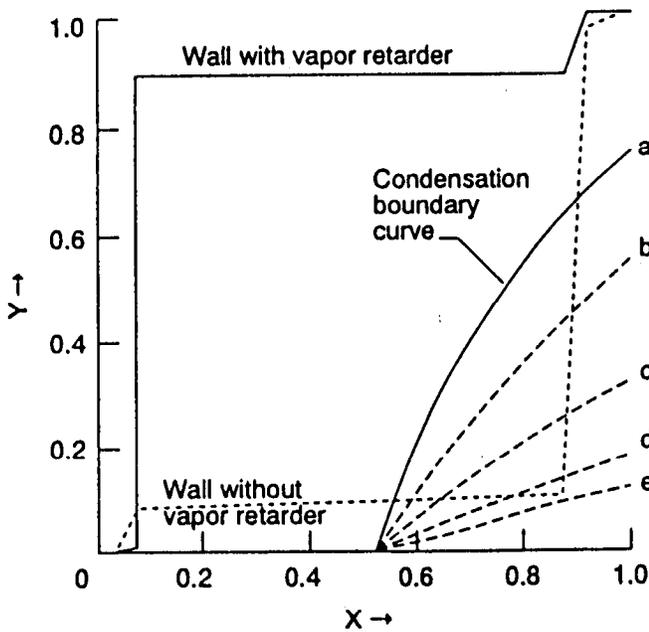


FIG. 5—Kieper diagram: example wall with and without vapor retarder, indoor conditions of 70°F (21°C), 40% RH and outdoor conditions of 20°F (-6.7°C), 50% RH.  $W_e Z$  values for the curves are (a) 0, (b) 0.2 in. Hg (677 Pa), (c) 0.5 in. Hg (1693 Pa), (d) 1.0 in. Hg (3386 Pa), and (e) 1.5 in. Hg (5080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

this allows analysis of walls or roofs under isothermal conditions, the model does not account for increased moisture movement within hygroscopic materials (wood, masonry) under temperature gradients. Many other models, discussed in other chapters, more accurately account for this and usually are more suitable for analysis of exterior walls and roofs containing hygroscopic materials.

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