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An Alternative Procedure for the Analysis of Data from the Cup Method Measurements for Determination of Water Vapor Transmission Properties

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ABSTRACT: The cup methods are used extensively to determine the water vapor transport characteristics of building materials. The dry cup method and the wet cup method prescribe two standardized procedures for this purpose. The dry cup method gives the results as an average value of the property at a mean relative humidity of 25% and the wet cup at 75%. This information is inadequate for detailed hygrothermal analysis of building components. The complete dependence of water vapor permeability on relative humidity is required by most of the current computer models used for hygrothermal analysis. This paper presents an extension of the cup methods in which a series of dry cup and another series of wet cup measurements are suggested at varying relative-humidity levels outside the cup. Also, a detailed procedure for the data analyses to define the dependence of vapor permeability on relative humidity is presented. The methodology is applied successfully to three materials: perlite insulation board, calcium silicate insulation board, and plywood sheathing.

KEYWORDS: water vapor transmission, permeance, permeability, relative humidity, dry cup, wet cup, hygroscopic

The dry and wet cup methods are used extensively to determine the water vapor transmission properties of building materials [1-5]. ASTM Standard Test Methods for Water Vapor Transmission of Materials (E 96) [6] prescribes the test procedure for these methods in which the specimen is sealed to the mouth of an impermeable test dish containing water or a desiccant and placed in a controlled atmosphere. Periodic weighing of the test assembly determines when a steady rate of weight loss or gain is attained, and this final rate, continued long enough to ensure its validity, is the primary test result. The rate together with the measured temperature and relative humidity (RH) of the controlled atmosphere and the area of the specimen is used to calculate the water vapor permeance of the specimen. According to existing ASTM Standard E 96, the dry cup test results give the vapor permeance at an average RH of 25% and the wet cup at 75%. The former is an average value between 0 and 50% and the latter between 50 and 100%. These average values will adequately represent a building

material from a material standard and quality control point of view. However, the information contained in such average values is inadequate from an analytical point of view. This is especially true in the case of hygroscopic building products. Also, all advanced computer models [7] for hygrothermal analyses need detailed input on the dependence of the water vapor transmission characteristics on the local relative humidity of all materials in a given building component. This paper revisits an experimental procedure proposed by Bazant and Najjar [8-10] and presents a method to analyze the data to satisfactorily determine the dependence of water vapor transmission properties on relative humidity.

Experimental Procedure

The experimental procedure is a logical extension of the existing procedure prescribed in ASTM E 96. Currently, the dry and wet cups assembled for the measurements are kept in an atmosphere maintained at 23°C and 50% RH. In the proposed extension one shall conduct two series of measurements. The first is a series of dry cup measurements and the second a series of wet cup measurements carried out as follows.

Many specimens are cut from a board or sheet of the building material being investigated. The physical characteristics of each specimen, such as its average thickness and bulk density, are determined. This gives an indication of the variability of the material. For most contemporary products investigated at the Institute for Research in Construction, the variability in the thickness is often within 1 to 2% of the mean thickness. But, depending on the product, the variation in the bulk density may be up to 10% of the mean value.

Two sets of specimens (minimum of three each) are randomly picked from the lot of specimens cut from the material. One set is used to make the dry cup assemblies according to ASTM E 96 and the other to make the wet cup assemblies. Care should be taken to maintain the thickness of the still air layer the same in all assemblies. Otherwise the corrections towards the resistances offered by the air layer complicate the data analysis. All assemblies are then placed in a chamber [5] maintained at 23°C and initially at approximately 30% RH. The assemblies are periodically weighed, as usual for the E 96 procedure, to confirm the steady state, and then the steady rate of mass change is recorded.

The above procedure is repeated for successively increasing levels of RH (at an increment of 10 to 15%) in the chamber. The dry cup measurements need not be done for RH above 70%, except

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for strongly hygroscopic materials. But the wet cup measurements should be continued to RH levels as close to 100% as practically possible. Usually this is about 95 to 97%. The two same sets of specimens may be used in the whole series of measurements. Alternatively, new sets of specimens may be used for every new RH level. If the same specimens are being used repeatedly, it is advisable to reassemble the cup after the measurements at each RH level. In the case of highly vapor-permeable specimens, this is especially important. If they are not reassembled, the desiccant may become too wet in the dry cup assemblies or the water level may change significantly in the wet cup assemblies. This should be prevented.

If the material under investigation is strongly hygroscopic, the dry cup measurements are continued to as high a chamber RH as practically possible. Then at the highest RH one set of wet cup measurements is conducted. As explained below, in this case the procedure for the data analysis will be slightly different.

Procedure for Data Analysis

The first step in the analysis is to confirm that each set of measurements was taken at a true steady state. This can be achieved by doing a linear least-squares analysis of the data on time versus mass change. The linear regression coefficient shall not be less than 0.998. From the slope one can determine the water vapor transmission rate for the corresponding test specimen at the corresponding RH level in the chamber. The area of the specimen shall be determined as prescribed in the ASTM standard. At times it may not be possible to maintain the temperature exactly equal to 3°C. If the variation is within 1 K, the measured value for the water vapor transmission rate shall be corrected to correspond to 3°C by assuming that the temperature dependence of the rate is identical to that for still air of the same thickness. This correction will be less than 1% (see Appendix).

Next, the water vapor transmission rate is plotted against the chamber RH. This will result in two separate but intersecting plots. The shape of the plots and the location of the point of intersection will depend on the nature of the material. If the material is nonhygroscopic, the two plots will be linear and will intersect at 50% RH. Furthermore, the magnitude of the slopes will be identical. This means that the water vapor transmission characteristic of the material does not depend on the local RH. This situation is illustrated in Fig. 1.

FIG. 1—Expected experimental results for a nonhygroscopic material.

FIG. 2—Expected experimental results for a hygroscopic material.

For a hygroscopic material, the results from the wet cup measurements will be invariably nonlinear. Also, the intersection of the two plots will be at an RH > 50%. This situation is illustrated in Fig. 2.

If the material is strongly hygroscopic the plots obtained from both series of measurements will be curved, and the point of intersection will be moved toward 100% RH. A proper definition of these curves demands measurements of both series up to the highest possible RH level. However, as stated earlier, a more practical approach is to conduct only the dry cup series in full and then one set of wet cup measurements at the highest chamber RH. The sum of the water vapor transmission rates from both sets of measurements at the highest RH will theoretically be equal to that for a dry cup measurement done at a chamber RH equal to 100%. Hence, this sum of the data combined with the data from the series of dry cup measurements will define the dependence of the water vapor transmission rate for the full range of RH.

Even for extremely accurate measurements, due to the inhomogeneity inherent to all building products, the plots will not be as smooth as shown in Figs. 1 and 2. The data should therefore be smoothed by curve fitting. The algebraic expression so obtained can be used to determine the derivative of the plot at any given RH. Then the permeance of the test assembly at that RH is given by:

$$\text{Permeance} = \frac{\text{Magnitude of derivative} \times 100}{\text{saturation water vapor pressure at } 23^{\circ}\text{C}}$$

The permeance so calculated should be corrected [5,11] for the surface resistances and the resistance offered by the still air inside the cups, common to all measurements. (This is why it is necessary to keep the thickness of the still air the same in all assemblies.) The corrected permeance multiplied by the average thickness of the material gives the permeability of the material at any given RH. Obviously, if a material behaves as shown in Fig. 1, there will be a unique value for the permeability of that material at 23°C.

Experimental Data on Three Materials

The procedure described above has been successfully applied to many building materials at the Institute for Research in Con-

TABLE

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Calcium silic
Plywood she

TABLE 2—

Chamber RH
%

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32.8
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55.8
74.7
74.7
74.7
82.1
82.1
82.1
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TABLE 1—Three building materials investigated in this work.

Material	Dry Density, kg·m ⁻³	Specimen Thickness, mm
Perlite insulation board	245 ± 6	20.0 ± 0.1
Calcium silicate insulation board	228 ± 2	19.6 ± 0.1
Plywood sheathing	430 ± 20	12.3 ± 0.1

TABLE 2—Water vapor transmission data for perlite insulation board.

Chamber RH, %	Dry Cup Results, kg m ⁻² s ⁻¹	Wet Cup Results, kg m ⁻² s ⁻¹
32.8	1.19E-06	...
32.8	1.18E-06	...
32.8	1.17E-06	...
47	1.99E-06	...
47	1.94E-06	...
47	1.87E-06	...
73.7	2.62E-06	...
73.7	2.56E-06	...
73.7	2.65E-06	...
32.6	...	2.59E-06
32.6	...	2.60E-06
32.6	...	2.72E-06
55.8	...	1.94E-06
55.8	...	1.84E-06
55.8	...	1.87E-06
74.7	...	9.37E-07
74.7	...	1.00E-06
74.7	...	1.08E-06
82.1	...	7.65E-07
82.1	...	7.01E-07
82.1	...	6.89E-07
93.5	...	2.94E-07
93.5	...	1.63E-07
93.5	...	2.00E-07

struction. As a demonstration, results on three materials listed in Table 1 are presented here.

The water vapor transmission rates measured on the specimens (a total of six specimens were used in the measurements on each material) are listed in Tables 2 to 4.

Least-squares analyses of the data in Tables 2 and 3 result in a smoothed set of data as shown in Figs. 3 and 4. The data on the perlite insulation board follow the pattern in Fig. 1. Hence it can be concluded that the water vapor permeability of the material is independent of RH. After all the corrections, the water vapor permeability of the material tested here is $(3.3 \pm 0.1) \times 10^{-11}$ kg m⁻¹ s⁻¹ Pa⁻¹. The wet cup results on the calcium silicate insulation board, however, show nonlinearity, and the plots resemble those in Fig. 2.

For the calcium silicate insulation board, it can be concluded that the water vapor permeability is constant at least up to RH 50%. From the linear portion of the plot this is equal to $(3.6 \pm 0.1) \times 10^{-11}$ kg m⁻¹ s⁻¹ Pa⁻¹. Above that it depends on the RH. The water vapor permeability of this material as a function of the RH, as obtained from the analysis of the wet cup results, is listed in Table 5.

The dry cup results on the plywood sheathing, a strongly hygroscopic material, are plotted in Fig. 5. As mentioned in the section on data analysis, the values at 100% RH are calculated as follows. An average value was calculated for the dry cup results at 89.6% RH. This average value was added to each of the wet cup results. Theoretically this sum corresponds to the dry cup results if one

were able to do it at a chamber RH equal to 100%. It is the sum of one measurement from 0 to 89.6% and another measurement from 89.6 to 100%, the sum being equivalent to one measurement from 0 to 100%.

A least-squares analysis of the results gives the smooth curve shown in Fig. 5. That smooth curve gives the water vapor permeabilities listed in Table 6.

Conclusions

The experimental data presented here show conclusively that the procedure suggested by Bazant and Najjar can be combined with existing ASTM Standard E 96 to determine the dependency of the water vapor permeabilities of building materials in a satisfactory way. The technique classifies building materials generally into

TABLE 3—Water vapor transmission data for calcium silicate insulation board.

Chamber RH, %	Dry Cup Results, kg m ⁻² s ⁻¹	Wet Cup Results, kg m ⁻² s ⁻¹
32.8	1.23E-06	...
32.8	1.22E-06	...
32.8	1.21E-06	...
47	2.00E-06	...
47	1.99E-06	...
47	2.08E-06	...
73.7	2.95E-06	...
73.7	2.86E-06	...
73.7	2.88E-06	...
32.6	...	3.22E-06
32.6	...	3.22E-06
32.6	...	3.30E-06
55.8	...	2.38E-06
55.8	...	2.36E-06
55.8	...	2.37E-06
74.7	...	1.45E-06
74.7	...	1.49E-06
74.7	...	1.65E-06
82.1	...	1.19E-06
82.1	...	1.19E-06
82.1	...	1.25E-06
93.5	...	5.18E-07
93.5	...	4.96E-07
93.5	...	5.50E-07

TABLE 4—Water vapor transmission data plywood sheathing.

Chamber RH, %	Dry Cup Results, kg m ⁻² s ⁻¹	Wet Cup Results, kg m ⁻² s ⁻¹
35	5.48E-08	...
35	4.37E-08	...
35	4.82E-08	...
52.3	1.13E-07	...
52.3	1.07E-07	...
52.3	1.01E-07	...
73.9	2.82E-07	...
73.9	2.56E-07	...
73.9	2.70E-07	...
89.6	6.13E-07	4.34E-07
89.6	5.60E-07	5.04E-07
89.6	4.69E-07	4.75E-07
100	9.82E-07*	...
100	1.05E-06*	...
100	1.02E-06*	...

* Sum of the mean dry cup results and individual wet cup results at RH = 89.6%.

three groups with respect to the dependence of their permeability on RH. For materials such as the perlite insulation board, the permeability may be regarded as independent of RH. For another group, such as the calcium silicate insulation board presented here, the permeability gradually increases with RH above 50%. For a third group, such as plywood, the permeability is a strong function of the RH. For such materials, it is advisable to carry out more measurements for the chamber RH between 85 and 97%. Otherwise the dependence of the permeability or RH may be ill-defined.

FIG. 3—Experimental data on the perlite insulation board.

FIG. 4—Experimental data on the calcium silicate insulation board.

TABLE 5—Water vapor permeability for calcium silicate insulation board.

Relative Humidity, %	Water Vapor Permeability, $\text{kg m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$
50	3.6E-11
60	3.8E-11
70	4.2E-11
80	4.8E-11
90	5.6E-11
100	6.7E-11

FIG. 5—Experimental data on plywood sheathing.

TABLE 6—Water vapor permeability for plywood sheathing.

Relative Humidity, %	Water Vapor Permeability, $\text{kg m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$
10	5.1E-13
20	6.6E-13
30	8.8E-13
40	1.2E-12
50	1.7E-12
60	2.6E-12
70	4.2E-12
80	7.5E-12
90	1.5E-11
100	4.1E-11

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APPENDIX

The Water Vapor Permeability of Stagnant Air: A Brief Literature Review

Introduction

Building physicists use a property called "vapor resistance factor," μ (dimensionless), to analyze the hygrothermal behavior of building materials and components. This property of any building material is defined as

$$\mu = \frac{\delta_a}{\delta} \quad (1)$$

where δ_a and δ are, respectively, the water vapor permeabilities of stagnant air and of the building material under consideration at identical temperature and pressure. The water vapor permeabilities of common building materials are measured reliably using the cup

method [1]. This method has been standardized for practical applications [6,13]. Due to various experimental difficulties, the water vapor permeability of stagnant air is not easily measurable. This quantity, as a function of temperature, T , is calculated from a knowledge of the binary diffusion coefficient, $D_{aw}(T)$, of air + water mixture as follows

$$\delta_a(T) = \frac{D_{aw}(T)}{R_v T} \quad (2)$$

where R_v is the ideal gas constant for the unit mass of water vapor.

The quantity $D_{aw}(T)$ is not well understood. This Appendix reviews the literature to determine its relative significance.

The Theoretical Approach

The partial pressure of water vapor in building physics applications is usually less than 3000 Pa. This is considerably less than the standard atmospheric pressure, namely, 101 325 Pa. Hence one may describe the diffusion process to be the diffusion of a "trace material" (water molecules) into a homogeneous medium (a binary mixture of nitrogen and oxygen) of fixed composition. Based on this assumption, theoretical methods can be used to calculate the binary diffusion coefficient for water in air through the following steps:

- Calculate the binary diffusion coefficient of water into oxygen.
- Calculate the binary diffusion coefficient of water into nitrogen.
- Calculate the binary diffusion coefficient of water into air by using a combining rule.

Kinetic theory of gases and statistical mechanics provides the complex theoretical background for the first two steps. However, a simple law called Blanc's law [14], provides the combining rule. For the present application, this law can be written as

$$\frac{1}{D_{aw}} = \frac{x_1}{D_{1w}} + \frac{x_2}{D_{2w}} \quad (3)$$

where

- x_1 = mole fraction of nitrogen in air,
- x_2 = mole fraction of oxygen in air,
- D_{1w} = binary diffusion coefficient of nitrogen + water, and
- D_{2w} = binary diffusion coefficient of oxygen + water.

The working equation for the first two steps listed above was derived independently by Chapman and Enskog [15] by solving the Boltzmann equation. If we consider two gases, A and B , with molecular masses m_A and m_B , the approximate equation (first-order approximation of the diffusion process) for their binary diffusion coefficient, D_{AB} is as follows [16]:

$$D_{AB} = \frac{3}{16} \frac{(4\pi kT/m_{AB})^{1/2}}{n\pi\sigma_{AB}\Omega_D} f_D \quad (4)$$

where

- m_{AB} = reduced mass, $2[(1/m_A) + (1/m_B)]^{-1}$,
- n = number density of molecules in mixture,
- k = Boltzmann constant,
- T = thermodynamic temperature,

f_D = a constant, 1 to 1.02 if m_A and m_B are of same order, and

σ_{AB} = arithmetic mean of collision diameters of A and B (e.g., from Lennard-Jones potential).

The quantity Ω_D in Eq 4 is called a diffusion collision integral for which various analytical approximations are found in the literature [15]. The accurate relation of Nufeld et al. [16] is

$$\Omega_D = \frac{A}{(T^*)^B} + \frac{C}{\exp(DT^*)} + \frac{E}{\exp(FT^*)} + \frac{G}{\exp(HT^*)} \quad (5)$$

where

T^* = reduced temperature, kT/ϵ_{AB} , ϵ_{AB} being geometric mean of characteristic energies of A and B (e.g., again from Lennard-Jones potential),

- $A = 1.06036$,
- $B = 0.15610$,
- $C = 0.19300$,
- $D = 0.47635$,
- $E = 1.03587$,
- $F = 1.52996$,
- $G = 1.76474$, and
- $H = 3.89411$.

According to this theoretical approach, we get the results shown in Table 7.

The vapor permeability values are quoted to two decimal places to show the theoretical dependence of δ_a on T . The absolute value cannot be that accurate due to the various approximations in the derivation of Eq 3. However, the order of magnitude is clearly established to be 10^{-10} . Now let us examine some experimental results.

Experimental Results

Marrero and Mason [17] have extensively reviewed the literature on gaseous diffusion coefficients up to 1970. It is seen that many researchers, from as early as 1882, have attempted to determine the binary diffusion coefficient for water + air mixture [17]. The agreement between various results, however, is not better than $\pm 10\%$. Within this uncertainty, Marrero and Mason gave the following equation for the binary diffusion coefficient of water + air at atmospheric pressure and between 282 and 450 K:

$$D_{aw}, (\text{m}^2/\text{s}) = 1.87 \times 10^{-10} T^{2.072} \quad (6)$$

TABLE 7—The water vapor permeability of stagnant air according to Chapman and Enskog, at various temperatures and 101 325 Pa pressure.

Temperature, °C	Permeability, kg/m·Pa·s	Temperature, °C	Permeability, kg/m·Pa·s
-50	1.18E-10	10	1.49E-10
-40	1.23E-10	20	1.54E-10
-30	1.29E-10	30	1.59E-10
-20	1.34E-10	40	1.64E-10
-10	1.39E-10	50	1.69E-10
0	1.44E-10	...	...

TABLE 8—The water vapor permeability of stagnant air according to Marrero and Mason, at various temperatures and 101 325-Pa pressure.

Temperature, °C	Permeability, kg/m·Pa·s	Temperature, °C	Permeability, kg/m·Pa·s
-50	1.33E-10	10	1.72E-10
-40	1.40E-10	20	1.79E-10
-30	1.46E-10	30	1.85E-10
-20	1.53E-10	40	1.92E-10
-10	1.59E-10	50	1.99E-10
0	1.66E-10	...	...

The water vapor permeabilities that correspond to Eq 6 are listed in Table 8.

It can be seen that the experimental results are consistently higher than those derived from theory. This is not unexpected because of various approximations made in the theoretical approach. Also, the temperature dependence shown by the two sets is slightly different. Marrero and Mason [17] have also given equations for the binary diffusion coefficients of water + oxygen and water + nitrogen based on experimental results in the literature. These coefficients in combination with Eq 3 also result in the permeabilities reported above.

Various other empirical correlations have also been suggested by different authors. These correlations are reviewed in the following section.

Empirical Correlations

Schirmer, Krischer, DeVries, and Vos have independently suggested equations [18] for the temperature dependence of the binary diffusion coefficient of water + air mixture. The water vapor permeabilities from these equations are calculated and listed in Table 9. Also included is a set of values based on atomic diffusion volumes according to Fuller et al. [15]. Once again, the theoretical values are consistently lower than those from the empirical correlations. However, except for those according to Krischer, the temperature dependence in all sets of results are almost the same.

Concluding Remarks

The review presented here suggests that the water vapor permeability of stagnant air has not yet been precisely determined. How-

TABLE 9—Water vapor permeability, kg/m·Pa·s, according to various empirical correlations.

Temperature, °C	DeVries	Schirmer	Krischer	Vos	Fuller et al.
-50	1.44E-10	1.55E-10	1.46E-10	1.48E-10	1.55E-10
-40	1.50E-10	1.61E-10	1.55E-10	1.54E-10	1.60E-10
-30	1.55E-10	1.66E-10	1.63E-10	1.60E-10	1.65E-10
-20	1.61E-10	1.72E-10	1.72E-10	1.66E-10	1.70E-10
-10	1.67E-10	1.77E-10	1.81E-10	1.71E-10	1.75E-10
0	1.72E-10	1.83E-10	1.90E-10	1.76E-10	1.80E-10
10	1.78E-10	1.88E-10	1.99E-10	1.81E-10	1.85E-10
20	1.83E-10	1.94E-10	2.08E-10	1.85E-10	1.90E-10
30	1.89E-10	1.99E-10	2.18E-10	1.89E-10	1.94E-10
40	1.94E-10	2.04E-10	2.27E-10	1.92E-10	1.99E-10
50	2.00E-10	2.10E-10	2.36E-10	1.96E-10	2.04E-10

ever, it is quite clear that its order is 10^{-10} , kg/m·Pa·s. Also, at 20°C, $\delta_a \approx 2 \times 10^{-10}$ kg/m·Pa·s. That is all that is presently known to us. Then, to continue to use the quantity called "vapor resistance factor," building physicists should consistently use one of the empirical correlations cited in this review. Many of the European standards [13] are currently using Schirmer's equation [19] for this purpose. The equation, which includes a correction for the pressure dependence as well, is

$$\delta_a = \frac{2.306 \times 10^{-5} P_0}{R_v T P} \left(\frac{T}{273.15} \right)^{1.81} \quad (7)$$

where

T = temperature (K),

P = ambient pressure (Pa),

P_0 = standard atmospheric pressure, i.e., 101 325 Pa, and

R_v = ideal gas constant for water, i.e., 461.5 J·K⁻¹·kg⁻¹.

Water vapor permeabilities of materials are usually determined at standard laboratory conditions. For practical applications the temperature dependence should be considered. In the physical environments in which buildings generally operate, a temperature range of -50 to +50°C may be seen by building materials in various parts of the building envelope. It may be assumed that the temperature dependence of the permeability in any medium is the same as that for air and necessary corrections be made for that dependence. Then Eq 7 is very useful.

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