Detailed Simulation of Combined Heat and Moisture Transfer in Building Components

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ABSTRACT

This paper discusses a theoretical analysis of combined heat and moisture transfer that includes both vapor and liquid transport mechanisms and their interactions. The physical meaning of various transport coefficients and their contribution to the overall transport phenomenon is addressed. A literature search on transport properties of building materials and their use in the combined heat and moisture transport is discussed.

The governing heat and moisture transport equations are solved in detail using the finite element method. Point heat and mass source terms are used in the governing equations to allow modeling of water leaks. The numerical solution scheme accounts for nonlinearity in the transport properties and accommodates one-, two- and three-dimensional elements. Therefore, a building component can be simulated in detail without making any configurational assumption.

A conventional wood frame wall is simulated in detail to demonstrate the effectiveness of the software. The effect of thermal bridges on total heat and moisture fluxes is discussed.

INTRODUCTION

Moisture transport in porous materials is a complex phenomenon. The major difficulties are associated with the fact that moisture migrates in each of its physical states and is driven by various vapor, liquid, and thermal forces. As a result, numerous treatments of moisture transport are found in the literature (Fortes and Okos 1980; Brake 1980). The main differences among theories stem from the selection of driving forces and their associated material properties. This paper discusses the availability of the various driving forces and suggests methods of interrelating them through modification of the fundamental properties.

The total moisture flow in a material may result from the vapor and liquid phases acting either in parallel or in series -- either in the same direction or in opposite directions. The transport can be attributed to various individual mechanisms. Knudsen diffusion, Stefan diffusion, and Poiseuille flow are usually the major vapor transport mechanisms and capillary flow, liquid diffusion, and surface diffusion are usually the major liquid transport mechanisms. Each mechanism affects and is affected by temperature gradients and each is a nonlinear function of material moisture content (Tveit 1966; Kohonen 1984). These mechanisms are well known and their mathematical formulations are well established (Kohonen 1984). Their individual contributions to the total flow and their interactions, however, are a function of the material properties in question.

To define each mechanism individually, accounting for its interactions, is mathematically cumbersome. Additionally, individual measurement of each mechanism's contribution as a separate entity has not yet been accomplished.
The most common treatment is to select a measurable driving force (e.g., vapor pressure or moisture content) and lump the separate mechanisms using a single overall effective diffusivity. This treatment can be improved upon by segregating the vapor and liquid transport mechanisms and lumping each separately. Vapor transport mechanisms can be defined by partial vapor pressure and liquid transport mechanisms can be defined by liquid pressure. The importance of maintaining this separation stems from the fact that vapor and liquid moisture flows are dominant at different levels of material moisture content.

At low relative humidity, moisture transfer takes place primarily in the vapor phase in porous materials. In this phase, moisture is mainly adsorbed on pore walls. As the moisture content increases, menisci begin to form in the pores. In capillary materials this leads to series transport of vapor and liquid. Water vapor condenses at one side of the meniscus, travels rapidly through a capillary tube, and evaporates from another meniscus. This phenomenon produces an apparent increase in vapor diffusivity.

At a critical moisture content, a continuous liquid phase develops and capillary suction dominates the rate of moisture flow. (The actual vapor diffusivity approaches zero when there is no longer a continuous gas phase.) Beyond the critical moisture content, the vapor transport is neglected. Anderson (1985) describes measurement of critical moisture content.

In addition to the selection of the driving forces, the use of the sorption isotherm and moisture retention curves affects the final governing equations for combined heat and moisture transport. In Luikov's theory (Luikov 1966) the sorption isotherm is used to obtain the isothermal moisture capacity. In Philip and De Vries' equations (Philip and De Vries 1957) it is used to obtain the thermal moisture diffusivity and thermal driving force. In liquid diffusivity theory it is used to relate the surface moisture content to surface partial vapor pressure (Fortes and Okos 1980).

In this paper the sorption isotherm and retention curves are used to relate the various driving forces and moisture capacities to each other. The resulting governing equations are solved by a detailed finite element code called Florida Software for Engineering Calculations (FSEC 1.1). Description of the software is given by Kerestecioglu et al. (1989). A conventional frame wall is simulated to demonstrate the effectiveness of the software.

**MATHEMATICAL FORMULATIONS**

Under isothermal conditions, diffusion of water vapor in air can be described by the Fick's law. If the total pressure, $P$, is assumed to be constant, and thermal diffusion (Soret effect) is considered to be negligible, the water vapor flux, $J_v$, can be written as:

$$ J_v = -D_v \frac{P(P-P_v)}{M(R T)} \nabla P_v $$

Equation 1 is known as the Stefan's law and its derivation is given by Holman (1976). In Equation 1, $D_v$ denotes the molecular diffusivity of water vapor in air and is defined by Sherwood and Pigford (1952):

$$ D_v = 9.26 \times 10^{-4} / P \frac{P^2}{(T+245)} $$

In porous materials water vapor does not diffuse through straight channels, it follows tortuous paths. Therefore, the water vapor diffusivity decreases; to express vapor diffusion in a porous material Equation 1 can be modified as (Philip and De Vries 1957; Luikov 1966):

$$ J_v = -\frac{D_a}{\rho_v} \frac{P(P-P_v)}{M(R T)} \nabla P_v = -D_v \nabla P_v $$

In Equation 3, $D_v$ denotes the vapor diffusivity. Using the ideal gas law, $P_v=\rho_v RT/M$, Equation 3 can be rewritten in terms of water vapor density (vapor concentration) as:

$$ J_v = -D_v \frac{RT}{M} \nabla \rho_v = -D_v \nabla \rho_v $$

The liquid flux, $J_l$, can be described by a modified form of Darcy's law (Klute 1952; Scheideger 1957):

$$ J_l = -D_l \rho_l \psi $$

In Equation 5, $D_l$ and $\psi$ denote the liquid diffusivity and the hydraulic potential, respectively. The hydraulic potential primarily consists of the gravitational potential ($\psi_g=\rho g h$) and the matric
potential \((v_m = P_1 / \rho_1)\). If the gravitational potential is neglected, Equation 5 can be rewritten as:

\[ J_1 = - D_1 \nabla P_1 \]  

(6)

The total moisture flux, \(J_{\text{tot}}\), is composed of vapor and liquid fluxes and can be written as:

\[ J_{\text{tot}} = - D_v \nabla P_v - D_1 \nabla P_1 = - D_\rho \nabla \rho_v - D_1 \nabla P_1 \]  

(7)

For a differential element, the equations for the conservation of mass in liquid and vapor phases can be written as:

\[ \rho_b \frac{\partial U}{\partial r} = - \nabla \cdot J_1 + Q_1 - m_{1v} \]  

(8)

\[ \lambda \frac{\partial \rho_v}{\partial r} = - \nabla \cdot J_v + Q_v + m_{1v} \]  

(9)

In Equations 8 and 9, \(m_{1v}\) represents the rate of evaporation. The total mass conservation equation can be obtained by adding Equations 8 and 9.

\[ \rho_b \frac{\partial U}{\partial r} + \lambda \frac{\partial \rho_v}{\partial r} = - \nabla \cdot J_1 - \nabla \cdot J_v + Q_1 + Q_v = - \nabla \cdot J_{\text{tot}} + Q_1 + Q_v \]  

(10)

For a differential element, the equation for the conservation of energy can be written as (Fortes and Okas 1978):

\[ (\rho C)_e \frac{\partial T}{\partial r} = \nabla \cdot (k_e \nabla T) + Q_c - (C_v \nabla J_v + C_1 J_1) \nabla T - \lambda m_{1v} \]  

(11)

Assuming the convective heat transfer term to be negligible compared to the conductive term, \(\nabla \cdot (k_e \nabla T) >> (C_v \nabla J_v + C_1 J_1) \nabla T\) (Luikov 1975), and substituting Equation 9 into Equation 10, the energy equation can be rewritten as:

\[ (\rho C)_e \frac{\partial T}{\partial r} + \lambda \frac{\partial \rho_v}{\partial r} = \nabla \cdot (k_e \nabla T) + Q_c + \lambda Q_v - \lambda \nabla \cdot J_v \]  

(12)

In Equations 10 and 12 there are four field variables -- the liquid pressure \((P_1)\), vapor pressure \((P_v)\), temperature \((T)\) and moisture content \((U)\). These field variables cannot be explicitly calculated from Equations 10 and 12. Therefore, in order to have a closure, additional relations or assumptions must be introduced. These closure relations and assumptions form the basis of most heat and mass transfer theories. Different closure relations are discussed below.

If local thermodynamic equilibrium is assumed to prevail, the sorption isotherm (in the hygroscopic region) or the moisture retention curve (in the capillary region) can be used to express a closure relation. The sorption isotherm and the moisture retention curve can be written by the following functional relations:

\[ U = U(P_v, T) \text{ or } U = U(P_v, T) \text{ in the hygroscopic region } 0 \leq \phi \leq \phi_{cr} \]  

(13)

\[ U = U(P_1, T) \text{ or } U = U(pF) \text{ in the capillary region } \phi \geq \phi_{cr} \]  

(14)

In Equation 14, \(pF\) denotes the logarithm of the suction force, \(F\), expressed in centimeters of head of water. In the capillary region, its value is proportional to the capillary pressure or liquid pressure, which can be determined experimentally by a tensiometer (Luikov 1965). In the hygroscopic region, the suction force is determined from the value of relative humidity, corresponding to the equilibrium moisture content of the material.

\[ pF = \log[-100P_1 Y_1/(Mg)] \]  

(15)

The sorption isotherm and the moisture retention curve can be defined by the following empirical equations (Kerestecioglu et al. 1988, Appendix D):

\[ U = a \phi^b + c \phi^d \text{ for } 0 \leq \phi \leq \phi_{cr} \]  

(16)

\[ U = a'pF^{b'} + c pF^{d'} \text{ for } \phi \geq \phi_{cr} \]  

(17)
The liquid pressure is related to the partial water vapor pressure through Kelvin’s equation (Anderson 1985):
\[
\frac{RT}{v_1} P_l = P_s + \frac{RT}{v_1} \ln \phi = P_s + \ln \frac{P_v}{P_s}
\] (18)

Using the sorption isotherm and the moisture retention curve (Equations 13 and 14), \(\nu P_v\) and \(\nu P_l\) can be expressed as a function of moisture content and temperature by Equations 19 and 20, respectively:

\[
\nu P_v = \frac{\partial P_v}{\partial U} \frac{\partial U}{\partial T} + \frac{\partial P_v}{\partial T} \frac{\partial T}{\partial U}
\] (19)

\[
\nu P_l = \frac{\partial P_l}{\partial U} \frac{\partial U}{\partial T} + \frac{\partial P_l}{\partial T} \frac{\partial T}{\partial U}
\] (20)

The partial derivatives of vapor and liquid pressures with relation to moisture content and temperature can be evaluated as follows:

\[
\frac{\partial P_v}{\partial U} = \phi \frac{\partial P_s}{\partial U} = \phi \frac{\partial P_s}{\partial \nu}, \quad \frac{\partial P_l}{\partial U} = \phi \frac{\partial P_s}{\partial U} + \phi \frac{\partial P_s}{\partial T} \frac{\partial T}{\partial U}
\] (21)

\[
\frac{\partial P_v}{\partial T} = \phi \frac{\partial P_s}{\partial T} = \phi \frac{\partial P_s}{\partial \nu} \frac{M \lambda}{RT^2} \frac{\partial T}{\partial U}
\] (22)

In Equation 21, \(\phi\) denotes the slope of the sorption isotherm and is known as the vapor differential capacity (Bomberg 1974). The differential \(dP_s/dT\) can be obtained from the Clausius-Clapeyron equation, \(dP_s/dT = \lambda MP_s/RT^2\) (De Vries 1987):

\[
\frac{\partial P_v}{\partial T} = P_s \frac{\partial P_s}{\partial T} + \phi \frac{M \lambda}{RT^2} P_s
\] (23)

where the saturation pressure, \(P_s\) can be approximated by Equation 24:

\[
P_s = \exp \left[23.7093 - 4111/(T-35.45)\right]
\] (24)

Using Equation 18, \(\partial P_l/\partial U\) can be written as:

\[
\frac{\partial P_l}{\partial U} = \frac{\partial P_l}{\partial T} \left(- \ln \phi\right) = \frac{\partial P_l}{\partial v_1} \frac{\partial v_1}{\partial U} \frac{\partial U}{\partial T}
\] (25)

If the moisture content is held constant, the pore-water meniscus would not change its contribution significantly. Therefore, the following equation may be written (Wilkinson and Klute 1962):

\[
\frac{\partial P_l}{\partial T} = \frac{\partial P_l}{\partial \sigma} \frac{\partial \sigma}{\partial T} = \gamma P_l
\] (26)

Using Equations 18 through 26, the vapor and liquid fluxes can be represented in terms of various driving forces by the following equations.

\[
J_v = -D_v \nu P_v = -D_v \nu P_v = (3D_l - D_D) \nu P_l - 3D_c \nu T
\] (27)

\[
J_l = -D_l \nu P_l = -D_l \nu P_l = (2D_v - D_D) \nu P_l - 2D_c \nu T = - (2D_v - D_v) \nu P_v - D_u \nu T
\] (28)
The diffusivities used in Equations 27 and 28 are defined in Table I. The total moisture flux can be represented in various combinations of Equations 27 and 28. These combinations and their associated diffusivities are given in Table 1. It should be emphasized that $D_v$ and $D_1$ are the fundamental diffusivities; the rest are derived from these using the given sorption isotherm, retention curve, and thermodynamical relations. Using the sorption isotherm, the storage terms ($\partial U/\partial T$ and $\partial p_v/\partial T$) used in Equation 10 can be expressed by the following equations:

\[
\frac{\partial U}{\partial T} = \frac{\partial U}{\partial T} - \frac{\partial U}{\partial T} = A_c \frac{\partial U}{\partial T} - B_p \frac{\partial U}{\partial T} - \frac{\partial U}{\partial T} = A_c \frac{\partial U}{\partial T} - B_p \frac{\partial U}{\partial T}
\]  

(29)

and

\[
\frac{\partial p_v}{\partial T} = \frac{\partial p_v}{\partial T} - \frac{\partial p_v}{\partial T} = \lambda \frac{\partial p_v}{\partial T} - \frac{\partial p_v}{\partial T} = \lambda \frac{\partial p_v}{\partial T} - \frac{\partial p_v}{\partial T}
\]  

(30)

where

\[
A_c = \frac{RT \xi}{P_{sM}} \quad \text{and} \quad C_u = \frac{P_{sM} \phi \lambda}{RT} \frac{T}{(T-35.45)}
\]  

(31)

Using the sorption curve defined by Equation 16, in the hygroscopic region, $A_c$ and $B_p$ are defined by the following equations:

\[
A_c = \frac{1}{P_{sM}} \left( \frac{1}{\phi} - \frac{\phi^b}{\phi} \right) \quad \text{and} \quad B_p = \frac{1}{\left( \frac{1}{\phi} - \frac{\phi^b}{\phi} \right)} \left( \frac{1}{\phi} - \frac{\phi^b}{\phi} \right)
\]  

(32)

Using Equations 29 and 30 and substituting the definition of $J_{tot}$ from Table 1, Equations 10 and 12 can be written in terms of various driving forces and associated diffusivities. One important point is that the driving forces used in the equations must be continuous at the material interfaces. For instance, if moisture content is used as one of the driving forces, a discontinuity at the material interfaces will be observed. Using the sorption isotherm or moisture retention curve, this discontinuity can be eliminated by relating the moisture content to vapor or liquid pressures, but the problem mathematically becomes more complicated. In the following governing equations, only continuous driving forces are used ($T$, $p_v$, $\rho_v$, and $P_t$). The following set of governing equations are used to define the conservation of moisture and energy.

\[
\nabla \cdot \left( \frac{\partial U}{\partial T} \frac{\partial p_v}{\partial T} \right) + \int_{\rho} \left( \frac{\partial U}{\partial T} + \frac{\partial p_v}{\partial T} \right) + Q + Q_v = \frac{\partial}{\partial T} \frac{\partial}{\partial T} \left( \frac{\partial U}{\partial T} \frac{\partial p_v}{\partial T} \right)
\]  

(33)

Equations 33 and 34 are applicable to both hygroscopic and capillary regions. However, along with these equations the sorption isotherm, moisture retention curve, and Kelvin's relation (as defined by Equations 13, 14 and 18) must be solved. In the hygroscopic region an alternate set of governing equations is given as follows:

\[
\nabla \cdot \left( \frac{\partial U}{\partial T} + \frac{\partial p_v}{\partial T} \right) + \int_{\rho} \left( \frac{\partial U}{\partial T} + \frac{\partial p_v}{\partial T} \right) + Q + \rho B_p = \frac{\partial}{\partial T} \frac{\partial}{\partial T} \left( \frac{\partial U}{\partial T} + \frac{\partial p_v}{\partial T} \right)
\]  

(35)

\[
\nabla \cdot \left( \frac{\partial U}{\partial T} + \frac{\partial p_v}{\partial T} \right) + \int_{\rho} \left( \frac{\partial U}{\partial T} + \frac{\partial p_v}{\partial T} \right) + Q + \rho B_p = \frac{\partial}{\partial T} \frac{\partial}{\partial T} \left( \frac{\partial U}{\partial T} + \frac{\partial p_v}{\partial T} \right)
\]  

(36)

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Equations 35 and 36 include the sorption curve and Kelvin's equation, thus making it easier to solve. In the capillary region it is preferable to use Equations 33 and 34 and in the hygroscopic region Equations 35 and 36 are preferred. Note that both sets of governing equations are derived using Equations 29, 30, and the definition of $J_{\tau \nu}$ from Table 1 in Equations 10 and 12. The thermal properties required by the equations are the effective thermal conductivity, specific heat, and density, whereas the moisture properties required are the vapor and liquid diffusivities, porosity, sorption isotherm, and retention curve (not required for the hygroscopic region).

The boundary conditions are given as follows:

$$-k_e vT + \lambda J_v = h_T (T - T_0) - q''_T + \epsilon \sigma (T_0^4 - T_g^4) + \pi \sigma F_{j-1} (T^4 - T_j^4)$$  \hspace{1cm} (37)

$$-D_v vP_v - D_p vP_p = h_v (P_v - P_{v,a}) - q''_v - q''_1$$  \hspace{1cm} (38)

$$-2D_v vP_v - 2D_p vT = h_p (P_p - P_{p,a}) - q''_v$$  \hspace{1cm} (39)

Equation 37 is the boundary condition for Equations 34 and 36. Equations 38 and 39 are boundary conditions for Equations 33 and 35, respectively. The convective moisture transfer coefficient, $h_p$, can be related to the convective heat transfer coefficient, $h_T$, through the Lewis relation, $h_p = h_T / (\rho_a C_p)$.

The transport coefficients required in the model can be measured by various methods. However, the description of these methods is beyond the scope of this paper. Some measurement methods and references describing them (with data sources) are given in Table 2. Using the data shown in Table 2, necessary transport coefficients can be obtained using the equations given in Table 1.

Equations 33 through 36, with the boundary conditions defined by Equations 37, 38, and 39, are solved using a finite element method. The governing equations are coupled and nonlinear in the material properties. Due to space limitations, details of the numerical solution procedure will not be given here. The numerical solution algorithms used in the combined heat and moisture transfer simulations are validated against closed-form solutions of certain simplified problems. Validation efforts and some closed-form solutions are reported by Dabir (1988) and Razzaq (1988).

RESULTS

A conventional wood frame wall has been simulated using FSEC 1.1. The wall components and the finite element mesh are depicted in Figure 1. Assuming symmetry, only half of the length of the wall section between two 2 by 4 studs is simulated. The gypsum drywall is assumed to be exposed to constant room conditions of $26.8^\circ$C and 55% relative humidity. The beveled wood siding is assumed to be exposed to ambient conditions corresponding to a typical July day in Miami. Hourly simulations are performed using the same 24-hour ambient data until periodic steady-state is attained. The material properties used in the simulations are taken from the references given in Table 2.

Temperature isotherms, total moisture flux vectors, partial vapor pressure, and liquid pressure contours at the end of selected hours are shown in Figures 2, 3, 4, and 5, respectively. The figures illustrate the power of numerical simulation as a research tool.

It is clear from the figures that the different materials comprising the wall section are significantly interactive. For example, the thermal capacitance of the stud wall as compared to the fiberglass insulation is clearly illustrated by the thermal islands shown in Figure 2 during the night and early morning hours. It is also clear that this capacitance effect is a major cause of the two-dimensional nature of the heat transfer.

A similar moisture capacitance effect can be seen in Figure 3, where significant moisture flux into and out of the wood stud over the course of the day is observed. During periods of wall heating (daytime) the most significant moisture fluxes are into the wood stud, and during periods of wall cooling (night) they are opposite, again indicating the significant moisture storage potential of the wood stud.

An additional observation of interest is the coupling between the heat and moisture transfer. One notes in Figure 3f that the moisture flux at the interior wall surface is inward at the stud
but outward at the wall center. This is due to the fact that the interior surface temperature is higher at the stud than the wall middle (see Figure 2f). Consequently, there is a sufficient partial vapor pressure gradient along the interior wall surface to cause the drywall to desorb moisture at the stud while simultaneously adsorbing moisture in the mid-wall area.

Figures 4 and 5 illustrate the behavior of the wall components with respect to the vapor and liquid pressure distributions. Again, the wood materials show significant differences from the fiberglass insulation. Figures 4c, d, and e show the propagation of the vapor pressure contours to be more rapid in the fiberglass than in the wood stud. Figure 5, on the other hand, shows less difference between the fiberglass and the stud with respect to the liquid pressure contours but does show the development of liquid pressure islands very similar to the thermal islands shown in Figure 2. This indicates again the significant moisture capacitance of the wood stud as compared to the fiberglass.

CONCLUSIONS

The use of detailed simulation capabilities can provide significant insight into complex physical phenomena. Building science problems too complex or expensive to study in depth experimentally can be more easily studied using numerical simulation techniques. Using FSEC 1.1 and the mathematical equations described above, very detailed information about combined heat and moisture transfer in an example wall was obtained. Other complex building science problems (moisture sorption, condensation, thermal bridging, etc.) can also be investigated in detail using this software. It must be emphasized, however, that it is difficult to obtain good quality material property data for use in such simulations. Even though large amounts of data have been compiled from the literature, there is little certainty as to their accuracy.

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NOMENCLATURE

\[ A_L = \frac{\partial u}{\partial p_w} \text{ [m}^3/\text{kg}] \]
\[ B_p = \frac{\partial u}{\partial T} \text{ [kg/kg.K]} \]
\[ C_e = \text{effective specific heat [J/kg.K]} \]
\[ C_{t1} = \text{specific heat of liquid water [J/kg.K]} \]
\[ C_{u} = \frac{\partial p_w}{\partial T} \text{ [kg/m}^3.\text{K]} \]
\[ C_p = \text{specific heat of air [J/kg.K]} \]
\[ C_v = \text{specific heat of water vapor [J/kg.K]} \]
\[ D_a = \text{molecular diffusivity of water vapor in air [m}^2/\text{s}] \]
\[ D_l = \text{liquid permeability coefficient [s]} \]
\[ D_v = \text{water vapor diffusivity based on partial vapor pressure [kg/m.s.Pa]} \]
\[ D_p = \text{water vapor diffusivity based on vapor density [m}^2/\text{s}] \]
\[ F = \text{suction force [cm of H}_2\text{O]} \]
\[ g = \text{acceleration due to gravity [9.807 m/s}^2\text{]} \]
\[ h = \text{height over a reference plane [m]} \]
\[ h_c = \text{convective heat transfer coefficient [W/m}^2.\text{K]} \]
\[ h_v = \text{convective moisture transfer coefficient (h}_v = h_{M/R/T} \text{ [s/m]} \]
\[ h_c = \text{convective moisture transfer coefficient [m/s]} \]
\[ J_{L} = \text{liquid moisture flux [kg/m}^2.\text{s]} \]
\[ J_{tot} = \text{total moisture flux [kg/m}^2.\text{s]} \]
\[ J_{V} = \text{water vapor flux [kg/m}^2.\text{s]} \]
\( k \) = thermal conductivity \([\text{W/m.K}]\)

\( M \) = molar weight of water \([18.016 \times 10^{-3}\ \text{kg/mol}]\)

\( P \) = total pressure \([\text{Pa} = \text{kg/m.s}^2]\)

\( P_1 \) = pore water pressure \([\text{Pa} = \text{kg/m.s}^2]\)

\( P_s \) = water vapor saturation pressure \([\text{Pa} = \text{kg/m.s}^2]\)

\( P_{v,a} \) = ambient partial water vapor pressure \([\text{Pa} = \text{kg/m.s}^2]\)

\( Q_{l} \) = internal liquid water generation rate \([\text{kg/m}^3\cdot\text{s}]\)

\( Q_t \) = internal heat generation rate \([\text{W/m}^3]\)

\( Q_v \) = internal water vapor generation rate \([\text{kg/m}^3\cdot\text{s}]\)

\( q_{l} \) = imposed liquid flux \([\text{kg/m}^2\cdot\text{s}]\)

\( q_t \) = imposed heat flux \([\text{W/m}^2]\)

\( q_v \) = imposed vapor flux \([\text{kg/m}^2\cdot\text{s}]\)

\( R \) = ideal gas constant \([8.3149\ \text{J/mol.K}]\)

\( r \) = radius of the capillary tube \([\text{m}]\)

\( T \) = temperature \([\text{K}]\)

\( T_s \) = sink or source temperature \([\text{K}]\)

\( T_\alpha \) = ambient temperature \([\text{K}]\)

\( U \) = moisture content on dry basis \([\text{kg/kg}]\)

\( v_1 \) = molar volume of liquid water \([18.016 \times 10^{-6}\ \text{m}^3/\text{mol}]\)

\( \gamma \) = surface tension \([\text{N/m} = \text{kg/s}^2]\) or Stefan-Boltzmann constant \([\text{W/m}^2\cdot\text{K}^4]\)

\( \sigma \) = time \([\text{s}]\)

\( \theta \) = tortuosity

\( \psi_e \) = relative humidity (water activity) \([0 \leq \psi_e \leq 1]\)

\( \psi_g \) = gravitational potential \([\text{J/kg} = \text{m}^2/\text{s}^2]\)

\( \psi_m \) = matrix potential \([\text{J/kg} = \text{m}^2/\text{s}^2]\)

REFERENCES


TABLE 1: Different Driving Forces and Corresponding Diffusivities Used in the Definition of Total Moisture Flux

<table>
<thead>
<tr>
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<th>First Driving Force's Diffusivity</th>
<th>Second Driving Force's Diffusivity</th>
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<tbody>
<tr>
<td>(J_{\text{tot}} = J_v + J_1)</td>
<td>(D_v = \frac{D_0 \cdot \Delta P}{\tau_0 \cdot (P_{\text{v}} - P)})</td>
<td>(D_1 = D_1)</td>
</tr>
<tr>
<td>(-D_v \cdot v_{P_v} - \frac{D_1 \cdot P_{\text{v}}}{v_{\text{T}}})</td>
<td>(D_2 = \frac{D_0 \cdot \Delta P}{\tau_0 \cdot (P_{\text{v}} - P)})</td>
<td>(D_2 = D_1)</td>
</tr>
<tr>
<td>(-D_0 \cdot v_{P_v} - \frac{D_1 \cdot P_{\text{v}}}{v_{\text{T}}})</td>
<td>(D_u = D_v + \frac{RT}{v_{\text{T}}})</td>
<td>(D_u = D_1)</td>
</tr>
<tr>
<td>(-D_0 \cdot v_{P_v} - \frac{D_1 \cdot P_{\text{v}}}{v_{\text{T}}})</td>
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<tr>
<td>(-D_0 \cdot v_{P_v} - \frac{D_1 \cdot P_{\text{v}}}{v_{\text{T}}})</td>
<td>(D_0 = \frac{D_0 \cdot \Delta P}{\tau_0 \cdot (P_{\text{v}} - P)})</td>
<td>(D_0 = D_1)</td>
</tr>
</tbody>
</table>

TABLE 2: Transport Coefficients Needed—Their Measurement and Data Sources

<table>
<thead>
<tr>
<th>Data</th>
<th>Measurement</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>(D_v)</td>
<td>Cup method</td>
<td>Anderson (1985), Tveit (1966), Bazant &amp; Najjar (1972) have proposed methods for evaluating (D_v) at discrete values of (\phi). For various materials, these references give (D_v = D_v(\phi)). Kohonen (1984) gives correlations between vapor diffusivity and air permeability of porous materials.</td>
</tr>
<tr>
<td></td>
<td>Air permeability</td>
<td></td>
</tr>
</tbody>
</table>

Note: There are several other direct and indirect measurement methods that are not listed in this table. Kohonen (1984) lists other measurement methods.
Figure 1. Schematic of conventional wood frame wall and mesh used in the simulation.
Figure 2. Temperature (°C) distribution history for frame wall
Figure 3. Total moisture flux (g/m²·h) distribution history for frame wall.
Figure 4. Partial water vapor pressure (kPa) distribution history for frame wall
Figure 5. Liquid water pressure (kPa) distribution history for frame wall