4201

EFFECT OF HYGROSCOPIC MATERIALS ON INDOOR RELATIVE HUMIDITY AND AIR QUALITY

M.K. West **E.C. Hansen**

ABSTRACT

One source of moisture-associated air quality problems is the proliferation of microbes on moist hygroscopic bodies within a space. Reduction of ventilation air can elevate material moisture content by disturbing building moisture balance. Methods to accurately predict material moisture content and sorption influence on building moisture balance are needed.

A moisture mass balance model was used to predict the effect of hygroscopic furnishings on indoor relative humidity. The objective was to model moisture mass transport in a structure and predict the magnitude and duration of material sorption. A rigorous moisture balance equation is solved analytically and numerically. A closed form simplification is used, along with material properties previously determined, to calculate relative humidity. Results show that hygroscopic furnishings can change humidity by 15% to 20% for as long as one month. It is concluded that hygroscopic furnishings should be considered when predicting indoor humidity.

INTRODUCTION

Reduction of the quantity of ventilation and infiltration air can change indoor air moisture content. This will occur when a weatherized structure operates with ineffective moisture control equipment—a common practice, especially in residences. A simple moisture mass balance of a structure indicates that the indoor air moisture content depends on the difference between moisture generation, influx, and desorption rate; and moisture removal and absorption rate. By reducing the influx of outdoor air, the removal (or influx) of moisture is reduced and indoor relative humidity increases (or decreases).

Building problems related in some manner to moisture can be grouped into four categories: (1) occupant immune reactions to microbes (including fungi) and their toxins, (2) transmission of infection via airborne viral matter, (3) structural degradation of the building itself, and (4) energy consumption for space air-conditioning.

Occurrence of upper respiratory illness is linked to relative humidity, as both human susceptibility and pathogen virility are influenced by air moisture content (Lester 1948; Lubart 1962). Growth and reproduction rates of fungus and mold increase with relative humidity (Block 1953). Pulmonary uptake of volatile organic compounds may decrease in dry air (Green 1982). Formaldehyde levels may be affected by relative humidity (Kusuda 1983). Relative humidity has an important influence on comfort and personal hygiene (Nevins 1966; Koch et al. 1960). Control of building relative humidity can reduce the occurrence of building-related illness, transmission and susceptibility to airborne pathogens, viability of decay fungi, and affect building energy use.

A problem encountered in attempting to properly control indoor relative humidity is performing an accurate moisture load calculation in order to optimize selection and operation of air-conditioning equipment. Practicable analysis methods for moisture mass transport on par with those of thermal transport are needed. It is unclear whether the influence of hygroscopic materials should be considered in predictions of indoor humidity (Fairey and Kerestecioglu 1985; Kusuda 1986; Kent 1966; Miller 1984).

The objectives of this work are to determine (1) the magnitude of the effect of hygroscopic furnishings on space air moisture content and (2) for what period of time those effects remain significant.

MODEL

Analysis of moisture transport in buildings begins by considering the moisture gains and losses of the structure. The dynamic balance of moisture gain and loss by the building air determines the relative humidity at any instant. An analysis must consider (1) ventilation and infiltration rates and the difference in moisture content of indoor and outdoor air; (2) internal moisture generation from bathing, cooking, humidifiers, etc.; (3) losses due to condensation and diffusion; and (4) absorption/desorption of moisture by hygroscopic materials within the space. Considering the space boundary to be a control surface, the following mass balance is written:

$$w\frac{dm_s}{dt} = m_o(i+V) - m_s(e+E) + g - c(m_s) - a(m_s, m_s') - d(m_s) \quad (1)$$

and by continuity

$$s = r + V - E \text{ and } E = V + i - e$$

where

a = sorption rate
c = condensation rate
d = diffusion rate through space boundary
E = exhaust airflow from HVAC to outside
e = exfiltration airflow from space to outside
g = generation rate
i = infiltration flow from outside to space
m_m = supply air moisture content
m_o = outside air moisture content
m_s = space air moisture content
r = return airflow from space to HVAC
s = supply airflow from HVAC to space
T_a = outside air temperature
T_s = space air temperature
V = ventilation airflow from outside to HVAC
w = space air volume

Sorption rate and diffusion rate can be positive or negative. For sorption $a = a(m_s, m_s', T_s)$, for condensation $c = c(m_s, T_s, T_a)$, and for diffusion $d = d(m_s, m_o)$. Mechanical humidification and dehumidification are modeled as a portion

M.K. West is a graduate assistant, and **E.C. Hansen** is an associate professor, Department of Mechanical Engineering, University of Florida, Gainesville.

of generation and condensation rates, respectively.

Simplification of Equation 1 is required to obtain an analytical closed-form solution. Three means of simplification will be explored. Each successive simplification produces a more useful relation but lessens the rigor of the analysis, of course. All three simplifications are required to arrive at a readily applicable analytical relation.

The first is to assume condensation, sorption, and diffusion exhibit the polynomial behavior:

$$c(m_s,T_s,T_a) = c_0 + c_1m_s + c_2m_s^2 + c_3m_s^3 + c^*(T_s,T_a) \quad (2a)$$

$$a(m_s,m_s',T_s) = a_0(t) + a_1(t)m_s + a_2(t)m_s^2 + a_3(t)m_s^3 + a^*(T_s) \quad (2b)$$

$$d(m_s,m_o) = d_0 + d_1m_s + d_2m_s^2 + d_3m_s^3 + d^*(m_o) \quad (2c)$$

The second simplification ignores the dependence of sorption on the rate of change of space air moisture content since sorption is only a weak function of this variable. Thus, Equation 2b is reduced to:

$$a(m_s,T_s) = a_0 + + a_1m_s + a_2m_s^2 + a_3m_s^3 + a^*(T_s) \quad (3)$$

The third successive simplification is an assumption of linear behavior of condensation, sorption, and diffusion with respect to space air moisture content. This assumption makes analytical solution uncomplicated, but it is quite severe and limits the rigor of the analysis. Using this treatment, results are only valid for small changes in space air moisture content. The following relations are obtained:

$$c(m_s,T_s,T_a) = c_0 + c_1m_s + c^*(T_s,T_a) \quad (4a)$$

$$a(m_s,T_s) = a_0 + a_1m_s + a^*(T_s) \quad (4b)$$

$$d(m_s,m_o) = d_0 + d_1m_s + d^*(m_o) \quad (4c)$$

The solution of Equation 1 using Equation 2 is begun by substitution and application of the initial conditions

$$at\ t = 0:\ V = E = e = r = s = 0$$

yielding Equation 1 as

$$\frac{dm_s}{dt} = A_0 - A_1m_s - A_2m_s^2 - A_3m_s^3 = F(m_s,t) \quad (5)$$

where

$$A_0 = k_0 - a_0(t) - c_0 - d_0$$
$$A_1 = k_1 + a_1(t) + c_1 + d_1$$
$$A_2 = a_2(t) + c_2 + d_2$$
$$A_3 = a_3(t) + c_3 + d_3$$
$$k_0 = m_o(i+V) + g$$
$$k_1 = e + E + r$$

The solution is had numerically or by means of the transformations

$$m_s(t) = A(t)Z(x) + B(t) \quad t = \int A^2(t)A_3dt$$

giving

$$\frac{dZ}{dx} = Z^3 + P(t)$$

$$\text{where } P(t) = \frac{1}{A^3(t)A_3}\left[A_0 - \frac{A_1A_2}{3A_3} + \frac{2}{27}\left(\frac{A_2^3}{A_3^2}\right) + \frac{1}{3}\frac{d}{dt}\left(\frac{A_2}{A_3}\right)\right]$$

$$A(t) = exp\ Q(t),\ Q(t) = \int\left(A_1 - \frac{A_2^2}{3A_3}\right)dt,\ B(t) = -\frac{A_2}{3A_3}$$

Employing Equation 3, Equation 1 reduces to the form

$$\frac{dm_s}{dt} = A_0 + A_1m_s + A_2m_s^2 + A_3m_s^3 = G(m_s) \quad (6)$$

thus the roots of $G(m_s) = 0$ are solutions of Equation 6 and the general solution is

$$(m_s - m_1)^a(m_s - m_2)^b(m_s - m_3)^c = Kexp(A_3t)$$

where m_1, m_2, and m_3 are roots of $G(ms) = 0$; a, b, and c are fixed constants; and K is an arbitrary constant.

Making use of Equation 4 results in $A_2 = A_3 = 0$ and Equation 1 is reduced to

$$\frac{dm_s}{dt} = A_0 + A_1m_s \quad (7)$$

Substitution yields

$$w\frac{dm_s}{dt} = m_o(i+V) - m_s(e+E) + g - c - a - d \quad (8)$$

and for the initial condition

$$m_s(0) = m_oi - m_se - a - d$$

the general solution is

$$m_s(t) = \alpha\ exp(-Mt) + \frac{N}{M}$$

where

$$wM = e + E$$
$$wN = m_o(i+V) + g - c - a - d$$
$$\alpha = \text{a constant of integration.}$$

A further substitution yields the form

$$m_s(t) = Dexp\left(-\frac{e+E}{w}t\right) + \left(\frac{m_o(i+V)+g-c-a-d}{e+E}\right) \quad (9)$$

$$\text{where } D = \frac{1}{e}\, m_oi(e-1) - (a+d)(e+1) - m_se^2$$

As t becomes infinite the steady-state moisture content is described by

$$m_s = \frac{m_o(i+V) + g-c-a-d}{e + E} \quad (10)$$

APPLICATION

A control volume analysis of building air moisture content was performed using the above equations, the material properties previously evaluated, and the following equations:

$$a = \frac{dU}{dt} = \frac{qm}{pR} \text{ for } t < t_{cr} \quad (11)$$

$$U = U_A\ exp(-kt) + U_f \text{ for } t > t_{cr} \quad (12)$$

where $U = u{\cdot}m$; u is the material moisture content; m is the mass of the hygroscopic body; t is time; p is density; R is volume-to-surface ratio; and U_A, U_f, q, and k are constants experimentally determined previously (West and Hansen 1989).

The analysis was performed for a model typical of a 2000 ft² home and a family of four. The descriptive parameters of the model are given in Table 1. The effect of hygroscopic furnishings was evaluated for the following process. For times less than zero: (1) space air conditions are 78°F (25.6°C), 85% RH; (2) the hygroscopic materials are at equilibrium; (3) $Q_s = Q_l = 0$; and (4) space air can mix with outdoor air (win-

TABLE 1A

Basic values used in moisture balance analysis, I-P units.

Variable	Value t > 0
infiltration rate	0.5 ach
infiltration, i	8000 ft³/hr
generation rate, g	1.2 lb_w/hr
AC condensation rate, C	4.0 lb_w/hr
outdoor temperature, T_a	80 F
space temperature, T_s	75 F
outdoor humidity, rh_a	65%
final indoor humidity, rh_f	48%
outdoor air moisture, m_o	0.014 lb_w/lb_a
final indoor moisture, m_f	0.009 lb_w/lb_a
sensible cooling, Q_s	11,780 Btu/hr
latent cooling, Q_l	3,865 Btu/hr
sensible infiltration, I_s	726 Btu/hr
latent infiltration, I_l	2,581 Btu/hr
transmural load, L	3,750 Btu/hr
solar load, S	5,200 Btu/hr
sensible generation, G	1,200 Btu/hr
sensible occupancy, O	900 Btu/hr

TABLE 1B

Basic values used in moisture balance analysis, SI units.

Variable	Value t > 0
infiltration rate	0.5 ach
infiltration, i	62.9 L/s
generation rate, g	0.54 kg_w/hr
AC condensation rate, c	1.81 kg_w/hr
outdoor temperature, T_a	26.7°C
space temperature, T_s	23.9°C
outdoor humidity, rh_a	65%
final indoor humidity, rh_f	48%
outdoor air moisture, m_o	0.014 kg_w/kg_a
final indoor moisture, m_f	0.009 kg_w/kg_a
sensible cooling, Q_s	3.452 kW
latent cooling, Q_l	1.132 kW
sensible infiltration, I_s	0.213 kW
latent infiltration, I_l	0.756 kW
transmural load, L	1.099 kW
solar load, S	1.5 kW
sensible generation, G	0.35 kW
sensible occupancy, O	0.26 kW

TABLE 2A

Furnishing parameters used in moisture balance analysis, I-P units.

Item	1/R[1/ft]	M [lb]	p[lb/ft³]	a[lb/hr]
bedding	2.7	160	3.1	0.077
clothes				
cotton	3.1	120	12.4	0.016
polyester	3.1	50	18.5	0.001
cushions				
cotton	4.3	14	1.9	0.017
urethane	3.1	48	2.5	0.006
wood	4.0	620	30.0	0.017
carpet	32.0	615	13.2	1.040
padding	48.0	375	11.8	0.488

TABLE 2B

Furnishing parameters used in moisture balance analysis, SI units.

Item	1/R[1/m]	M [kg]	p[kg/m³]	a[kg/hr]
bedding	8.6	72.6	49.6	0.0349
clothes				
cotton	10	54.4	199	0.0073
polyester	10	22.7	296	0.0005
cushions				
cotton	14	6.35	30.4	0.0077
urethane	10	21.8	40.0	0.0027
wood	13	280	480	0.0077
carpet	100	280	211	0.472
padding	160	170	189	0.221

dows open). At time zero: (1) the air mixing is terminated (windows closed), and (2) Q_s and Q_l take on the values listed in Table 1 (AC operational). To force a conservative prediction of the length of time hygroscopic furnishings affect indoor humidity, the hygroscopic materials experience rh_f for all $t > 0$. The furnishing materials used in the analysis are described in Table 2.

To characterize the effect of the furnishings on indoor humidity, the following parameters were calculated: (1) the constant rate period desorption rate, a_{cr}; (2) the desorption rate after 99% of the sample's total desorbed moisture has transferred to the space, a_{99}; (3) the time required to reach the end of the constant rate period, t_{cr}; (4) the time required for the desorption rate to reach an ineffectual level, t_a; and (5) the time required for 99% of the sample's total desorbed moisture to enter the space, t_{99}. The ineffectual desorption rate is defined as the rate which does not affect indoor humidity by more than 1%, a_a = 0.08 lb/h (0.035 kg/h) total for all materials combined. For each material individually, the value of a_a depends upon the number and intensity of other materials still desorbing. A negligible desorption rate of a_a = 0.01 lb/h (0.005 kg/h) is assumed for each material. The calculated parameters are given in Table 3. Values for a_{cr} are equal to a in Table 2.

DISCUSSION

The findings differ by as much as two orders of magnitude among materials. This correlates well with results reported in the literature, which show hygroscopic effects lasting from a few hours (Miller 1984) to many months (Kent 1966).

The carpet had the highest initial (1.040 lb/h, 0.4712 kg/h) and 99% (0.035 lb/h, 0.0159 kg/h) desorption rates. The rates reported for the carpet are effective rates since a portion of its available drying intensity was used by the underlying padding; padding desorption into the space must transpire through the carpet. The padding's initial and 99% desorption rates were roughly one-half the carpet's. The polyester clothing had a negligible desorption rate.

The wood had by far the largest time parameter values. It took approximately 100 days to reach U_{cr}, 122 days for its desorption rate to reach 0.01 lb/h (0.005 kg/h), and 246 days for 99% of total desorbed moisture to enter the space. In contrast, the time parameter values for the cotton clothing were approximately 8 days to reach U_{cr}, 9 days for its desorption rate to become 0.01 lb/h (0.005 kg/h), and 19 days for 99% desorption. The quickest response was displayed by the carpet; it reached U_{cr} in 7 hours, 0.01 lb/h (0.005 kg/h) desorption rate in 21.2 hours, and 99% desorption in 17.3 hours.

The indoor relative humidity for the model was increased from 48% to 64% by hygroscopic desorption. As desorption rates fell, relative humidity dropped to within 1% of its final equilibrium value after 30 days. The principal contributors to desorbtion as the model proceeded are listed in Table 4. After 2 days, wood became the principal contributor to desorbed air moisture within the space; it was responsible for 60% of

TABLE 3A

Parameters characterizing sorbtion effects on air moisture content, I-P units.

Item	a_{99}[lb/hr]	t_{cr}[hr]	t_{s}[hr]	t_{99}[hr]
bedding	0.00257	22.7	42.6	55.8
clothes				
cotton	0.00053	188.1	226.0	462.4
polyester	0.00002	311.1	0.0	764.6
cushions				
cotton	0.00054	17.3	21.2	42.9
urethane	0.00022	52.3	0.0	126.6
wood	0.00055	2405.5	2921.4	5909.1
carpet	0.01823	7.0	21.0	17.3
padding	0.01627	13.2	35.2	32.4

TABLE 3B

Parameters characterizing sorbtion effects on air moisture content, SI units.

Item	a_{99}[kg/hr]	t_{cr}[hr]	t_{s}[hr]	t_{99}[hr]
bedding	0.00116	22.7	42.6	55.8
clothes				
cotton	0.00024	188.1	226.0	462.4
polyester	0.00001	311.1	0.0	764.6
cushions				
cotton	0.00024	17.3	21.2	42.9
urethane	0.00010	52.3	0.0	126.6
wood	0.00025	2405.5	2921.4	5909.1
carpet	0.00827	7.0	21.0	17.3
padding	0.00738	13.2	35.2	32.4

TABLE 4

Materials having the dominant effect on indoor relative humidity after time t and their responsible fraction of humidity increase over 48%.

t[hr]	rh_s[%]	materials (fraction)
0	64	carpet (.63), padding (.29), bedding (.04)
48	52	wood (.60), cotton (.34), cushions (.03)
120	50	wood (.79), cotton (.20), polyester (.03)
720	49	wood (1.00)
920	48	—

all desorbed airborne moisture. After 30 days, wood was the only material with a significant desorption rate. After 38 days, the wood desorption rate dropped to 0.07 lb/h (0.032 kg/h) and it no longer affected the indoor relative humidity of the model.

CONCLUSIONS

The model shows that hygroscopic bodies can have a significant effect on air moisture content. The period of the effect depends on the body's surface-to-volume ratio and density as well as its hygroscopic properties. Indoor relative humidity can be changed on the order of 15% to 20% by a combination of hygroscopic bodies typical of residential furnishings. This change in relative humidity is supported by materials having both short- and long-term effects on space air moisture content.

Of the materials tested, the nylon pile jute-backed carpet and urethane rubber composite padding increase relative humidity the most in a simple model analysis. However, their effects last only two days. Sorption by wood causes an appreciably weaker but longer-lasting deviation in indoor relative humidity. The effects of wood can last on the order of one month. Hygroscopic materials should be considered when predicting indoor relative humidity.

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