ALGORITHMS TO PREDICT DETAILED MOISTURE EFFECTS IN BUILDINGS

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ABSTRACT

Buildings exhibit thermal as well as moisture capacitance. In humid climates, predictions of building cooling loads and indoor humidity may be in significant error if building moisture storage is ignored. A **M**oisture **A**dsorption and **D**esorption model (MAD) has been developed to evaluate the effects of moisture transport in buildings. The model uses a set of differential and algebraic equations to define the combined thermal and mass transfer in buildings. Indoor moisture concentration is modeled as a function of its primary driving forces. The driving forces are modeled simultaneously using detailed numerical solutions that account for their dynamic, interrelated reactions.

The model has been validated through experimental data in residential attics and in actual residences. The paper presents the algorithms and sources of input data, describes the validation effort, and discusses future research needs in this area.

INTRODUCTION

Research of building moisture problems has been primarily limited to northern cold-weather problems. As a result, the emphasis has been on the problems of condensation on or within building components. This research has concentrated on vapor diffusion through building materials and has resulted in recommendations for the placement of vapor barrier materials within building envelopes.

In humid climates under summer conditions, vapor diffusion through building envelopes is not a significant problem. The overwhelming majority of building moisture arrives in the conditioned zone through infiltration and internal generation (ASHRAE 1981, p.26.31). Additionally, condensation of moisture in building materials in summer is a rare occurrence that does not constitute a serious problem in these climates (Sherwood 1985). Ambient dew-point temperatures only rarely exceed internal dry-bulb temperatures and then only for relatively short periods of time.

There are, however, significant moisture problems associated with warm, humid climates. It is not uncommon in severely humid climates to have moisture loads in excess of 50 pounds per day (21.8 kg/day). In typical residences, these loads are removed by the air-conditioning system and do not generally cause serious problems. In passively cooled or energy-efficient buildings with standard air conditioners where sensible loads have been significantly reduced, these moisture loads may result in excessive relative humidity levels, even in air-conditioned buildings. Sustained relative humidities (RH) of 70% or greater will lead to the growth of molds and mildews (Humphries 1972). Sustained RH levels in the high sixties and above also cause accelerated growth of bacteria, fungi, mites, etc. (Sterling 1985).

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Methods of accurately evaluating moisture effects in buildings are generally lacking in building energy analysis procedures. Typically, simple procedures call for the calculation of sensible loads and the subsequent application of some percentage of that load to represent the additional moisture load of the zone. Where moisture loads are calculated by detailed procedures, the assumption is usually made that all moisture entering the zone is added to the zone air and none is adsorbed by the building furnishings, etc.

This assumption can produce inaccuracies. In reality, the moisture that is added to a conditioned zone will be distributed in some manner between the zone air, the zone materials, and the zone mechanical system. The significant impact of moisture adsorption and desorption by zone material has also been recently recognized by other researchers (Kusuda 1983; Miller 1984).

The moisture-removal performance of an air conditioner strongly depends on the evaporator coil inlet's wet-bulb temperature. If all moisture loads are assumed to go to the zone air, then errors in machine performance characteristics will be made, even in detailed machine analysis procedures. Depending on building control strategies, these errors can produce significant inaccuracies, particularly in hourly calculations of zone loads, indoor humidities, and human comfort.

For accurate evaluation of moisture loads, it is recommended that these criteria be met:

- Building material moisture adsorption and desorption properties should be modeled to correctly calculate wet-bulb temperature of air entering the machine and accurate infiltration loads.

- Machine sensible and latent cooling performance should be calculated during the building simulation at each hour, accounting for the variation within the hour of air conditions entering and leaving the cooling coil as it removes moisture.

- Accurate modeling of on/off thermostats in residences, which cycle the air conditioner a number of times in an hour. The cycling and transient performance caused by the cycling need to be accounted for to obtain accurate predictions of humidity and energy consumption.

THEORETICAL APPROACH

The governing moisture balance equation in a given zone, i, may be written as follows (please see nomenclature for explanation of symbols).

$$m_i(dWr_i/dt) = +MGR_i - \sum_{k=1}^{nzm} MAC_{i,k} + \sum_{k=1}^{nzm} REV_{i,k} + INF_i$$

$$+VEN_i + MIX_i - \sum_{k=1}^{nzc} CON_{i,k} - \sum_{k=1}^{nze} EMAD_{i,k} - \sum_{k=1}^{nzf} FMAD_{i,k} \qquad (1)$$

Equation 1 describes the conservation of moisture in a control volume (room), and all the moisture sources and sinks that affect the room moisture balance are depicted in Figure 1. The significance of each term appearing on the right-hand side of Equation 1 starting with the first term is explained below.

1. MGR is the internal moisture generation rate and it is a strong function of the occupancy level and the habits of the occupants. Respiring, cooking, drying clothes, showering, and having indoor plants are among the largest contributors. ASHRAE data indicate that taking a shower can add 0.44 pounds (0.2 kg) of water to the air; cooking and diswashing can add from 1.1 pounds (0.5 kg) at breakfast to 3.31 pounds (1.5 kg) of water at dinner.

2. MAC is the amount of moisture that is removed by cooling equipment. It corresponds to the latent cooling performance of equipment. The moisture is removed by an air conditioner unit during the removal of sensible load if the coil is below the dew point of the entering air. However, a stand-alone dehumidifier or the combination of both units can also be used in order to remove the moisture from the conditioned space. Consequently, the summation sign in front of this term designates these different units. In the case of humidification modeling, the desired amount of moisture input can be handled through this term. Generally the dehumidification (latent load removal)

performance of a mechanical system can be represented by algebraic equations such as in Equation 2.

$$MAC_{i,k} = f(TD_o, TDr_{i,k}, TWr_{i,k}) \tag{2}$$

However, if data are available, more detailed functional relations (using different independent variables) can also be used. For instance, when an air conditioner unit comes on, its latent load removal performance is poor compared to its steady-state performance. Therefore, by having two sets of conditions, one representing the dynamic and the other one representing the steady-state performance, the moisture removal rate due to the air conditioner operation can be modeled. At this point, more can be said about the modeling techniques of this term; however, due to space limitations, that aspect will be explained in future papers.

3. REV is the amount of moisture that is reevaporated into the conditioned space from the mechanical cooling or dehumidification coil surfaces and their condensate collection pans. This term is dictated by the velocity field prevailing over the cooling coils and condensate pans. The amount of moisture that is added into the zone by reevaporation can be estimated by Equation 3. This term can be significant, especially in the case of continuous fan operations.

$$REV_{i,k} = hmL_{i,k}\, Acp_{i,k} (Wsa_{i,k} - Wsu_{i,k}) \tag{3}$$

4. INF represents the amount of moisture that is brought into or removed from the zone by infiltration. If the infiltration and exfiltration rates are known, the magnitute of this term can be calculated using the following equation.

$$INF_i = IACH_i\, m_i\, Wa - EACH_i\, m_i\, Wr_i \tag{4}$$

5. VEN represents the amount of moisture that is brought into or removed from the zone by ventilation, and its magnitute is given by

$$VEN_i = IVACH_i\, m_i\, Wa - EVACH_i\, m_i\, Wr_i \tag{5}$$

6. MIX represents the amount of moisture that is brought into or removed from a given zone by the internal flows between connected zones. For instance, if the kitchen or bathrooms are separated from the living areas, the moisture that is heavily generated in these sections will be diffused and convected to the living areas. If the internal mass flow rates between the connected zones are known, the amount of moisture that is brought into or removed from the zone can be calculated by

$$MIX_i = \sum_{\substack{j=1 \\ j\neq i}}^{nz} IMACH_{i,j}\, m_i\, Wr_j - \sum_{\substack{j=1 \\ j\neq i}}^{nz} EMACH_{i,j}\, m_i\, Wr_i \tag{6}$$

7. CON represents the amount of moisture that can condense over the cold surfaces in the zone and is described by the following equation.

$$CON_{i,k} = hc_{i,k}\, Ac_{i,k}\, (Wr_i - Wc_{i,k}) \tag{7}$$

8. EMAD represents the amount of moisture that is adsorbed or desorbed by the envelope walls. Envelope walls with different moisture adsorption and desorption characteristics have to be simulated separately. Envelope moisture diffusion is also accounted for with this term.

9. FMAD represents the amount of moisture that is adsorbed or desorbed by the internal furnishings and internal mass.

The main thrust of this paper is to present a procedure to account for EMAD and FMAD based on physical principles and material properties. An alternate, simpler procedure will be to set EMAD and FMAD to zero in Equation 1 and artificially increase m_i of Equation 1 so that an equivalent "moisture capacitance" is modeled. Such a procedure is also currently under development at FSEC. However, we note that considerations such as presented below will also have to serve as a basis for development of numerical values for simple moisture capacitance of building zones.

Moisture Adsorption and Desorption (MAD)

If a capillary porous or hygroscopic material is exposed to humid or dry air, the material will adsorb or desorb moisture. If the material is exposed to such conditions, eventually it will come into thermodynamic and molecular equilibrium with the environment. Many building materials are capillary porous or hygroscopic, and indoor humidity conditions can be highly dynamic especially for ventilated buildings. Therefore, these materials have enormous moisture adsorption and desorption potentials.

The mathematical modeling of moisture adsorption and desorption characteristics of materials is complex. Moisture and heat transfer equations for the material side and moisture, heat, and momentum transfer equations for the fluid side have to be simultaneously considered. It also has to be emphasized that heat and moisture transport in materials are inseparable and interdependent. Detailed mathematical descriptions of these governing equations can be found in a recent study by Kerestecioglu (1985). In this detailed study, the governing equations are solved using a three-dimensional finite element program called FEMALP (Kerestecioglu 1985).

In this paper more simplified equations are employed to estimate MAD characteristics. However, in order to execute these equations, certain material parameters must be known. These parameters may be obtained from a detailed computer code such as FEMALP or from experimental data. The following equations represent the wetting and drying (MAD) rates of the envelope walls and the internal furnishings of a room, respectively.

$$EMAD_{i,k} = dMce_{i,k}/dt = hme_{i,k}\, Ame_{i,k}(Wr_i - Wse_{i,k}) \tag{8}$$

$$FMAD_{i,k} = dMcf_{i,k}/dt = hmf_{i,k}\, Amf_{i,k}(Wr_i - Wsf_{i,k}) \tag{9}$$

The objective of this analytical procedure is to match the experimental or theoretical MAD rates through Equations 8 and 9. To accomplish this, two distinct steps have to be followed.

1. The right-hand side of Equations 8 and 9 represents the convective moisture transfer occuring between the material surface and the room air. However, in order to model the convective mass transfer fluxes, the humidity ratio of the air at the material surface has to be determined. Note that this is different from the room air humidity ratio and is the reason why moisture adsorption/desorption happens. A thin boundary layer of surface air is assumed in this model, and we assume that the solid is in moisture equilibrium with this thin boundary layer air. Figure 2 gives the equilibrium moisture content of some building materials for certain relative humidity ranges. The moisture equilibrium data are given for a constant temperature in terms of the moisture content of the material and relative humidity of the air. If a material is exposed long enough to a constant air relative humidity, its moisture content will attain a specific value. At the equilibrium point, thermodynamic and molecular equilibrium will exist and the humidity ratio of the room air and the humidity ratio of the air at the material surface will be identical, hence,

   $$Wse = Wr \quad \text{and} \quad Wsf = Wr.$$

   The RH can be expressed with the following approximation:

   $$RH \simeq (Wse/Wsa)_{TD} \text{ or } RH \simeq (Wsf/Wsa)_{TD} \tag{10a}$$

   where W_{sa} represents the humidity ratio of the air at saturation,

   <u>and</u>

   $$Wsa = f(BP,TD) \tag{10b}$$

   From the equilibrium moisture data, the following functional relation can be obtained:

   $$Ue = f(RH,TD) \tag{11}$$

   Substitution of Equations 10 into Equation 11 gives

   $$Ue = f(Wse,Wsa,BP,TD) \tag{12}$$

   However, at a given surface temperature (TD) and barometric pressure (BP) (where Wsa can be calculated), the moisture content may be represented as a function of only Wse and vice versa.

$$Ue = f(Wse) \quad \text{or} \quad Wse = f(Ue) \tag{13}$$

Consequently, by curve fitting the equilibrium data using piece-wise linearization, the moisture content of the material can be directly related to surface conditions. The following equations can be used to represent these functional relations:

$$Wse_{i,k} = A1e_{i,k}\, Uee_{i,k} + A2e_{i,k} \tag{14}$$
$$Uee_{i,k} = Mce_{i,k}/Mde_{i,k} \tag{15}$$
$$Wsf_{i,k} = A1f_{i,k}\, Uef_{i,k} + A2f_{i,k} \tag{16}$$
$$Uef_{i,k} = Mcf_{i,k}/Mdf_{i,k} \tag{17}$$

If the behavior of the equilibrium isotherms is not smooth, higher order relations may be preferred. However, all materials will have unique coefficients (e.g., A1, A2, ... , An) corresponding to unique temperature regimes. For instance, for cork at 95 F (35°C) (data given in Figure 2) Equation 14 with piece-wise linearization can be written as

$$Wse = 0.49008\ Uee - 0.00196 \quad \text{for} \quad 0.034 \leq Uee < 0.049$$
$$Wse = 0.27227\ Uee + 0.00871 \quad \text{for} \quad 0.049 \leq Uee < 0.076$$

and

$$Wse = 0.14137\ Uee + 0.01866 \quad \text{for} \quad 0.076 \leq Uee \leq 0.128$$

It should be emphasized that the above argument, which uses the moisture equilibrium data to represent the air humidity at the material surface conditions, does not state that the material is in equilibrium with the room air but that it is in equilibrium with the boundary layer air at the room surface. Thus, it relates the moisture content of the material to the material surface humidity conditions (e.g., at a low material moisture content the material surface humidity will also be low).

2. In Equations 8 and 9 the surface areas are fixed and, for a given velocity regime, the convective mass transfer coefficients are also fixed. The convective mass transfer coefficient can be calculated from Lewis relations. Lewis relation expresses the relative rates of propagation of energy and mass within a system. For low mass transfer rates the convective mass transfer coefficient can be related to the convective heat transfer coefficient through the following equation:

$$hm = h_T/Cp \tag{18}$$

The Lewis relation is valid for turbulent flows; however, for laminar flows, deviations from Lewis relations can be observed (Kerestecioglu 1985).

Consequently, one way of matching experimental or detailed theoretical MAD rates is to vary the material dry weight (Mde and Mdf) that effectively participated in MAD. The effective material dry weights for the envelope walls and internal furnishings may be calculated with the following relations:

$$Mde = \rho Ame\ Lde \quad \text{and} \quad Mdf = \rho Amf\ Ldf \tag{19}$$

In Equation 19 Lde and Ldf represent the effective MAD layer thickness associated with the envelope walls and the furnishings, respectively. In reality, if a dry material is exposed to highly moist conditions, the moisture will begin to migrate through the material. At the surface of the material, the moisture content will attain its highest magnitude. Moving inward from the surface, its magnitude will reduce. However, when using Equations 8, 9, and 14 through 17 the entire MAD surface layer is lumped and assumed to have a uniform moisture content; hence, it is necessary to determine an effective MAD layer thickness. In order to clarify and varify the steps explained above, the following example is considered.

A 0.0328 feet (0.01 m) thick cement paste slab is used as an internal storage mass. The slab is exposed to indoor conditions from both sides. The effective MAD layer thickness is to be estimated from the following data:

$Wr=0.0022\ lb_W/lb_D\ (0.0022\ kg_W/kg_D)$;
$\rho=137.3\ lb_D/ft^3\ (2200\ kg_D/m^3)$;
$hmf=0.59\ lb_D/ft^2.h\ (2.9\ kg_D/m^2.h)$;
$Mcfo=5.054\ lb_W\ (2.2924\ kg_W)$;

$TD=77^oF$ (25^oC) and $Amf=10.7639$ ft^2 (1.0 m^2).

The detailed theoretical drying rate of the material is depicted in Figure 3 (Huang 1979). The equilibrium moisture content curve of the cement paste is given in Figure 4 (Huang 1979). The curve depicted in Figure 4 can also be represented with the following equations:

$$Uef = 0.039 + 0.14 \ RH \text{ or } Uef = 0.039 + 0.14 \ Wsf/Wsa$$

However, at 77 F (25^oC) $Wsa=0.02017$ lb_W/lb_D (0.02017 kg_W/kg_D), therefore,

$$Wsf=-5.6188 \ 10^{-3} + 0.1441 \ Uef \text{ with } Uef=Mcf/Mdf \qquad (20)$$

Substituting Equations 19 and 20 into Equation 8 and using the drying rate data given in Figure 3, Equation 8 may be solved for the effective MAD thickness (Mde). The effective MAD thickness for each side of the cement paste slab under the above conditions is estimated to be 0.19 inches ($4.8*10^{-3}$ m). The drying rate results obtained through Equation 8 are depicted in Figure 3.

It should be emphasized that the MAD model presented above is applicable only for cases where no seasonal or long term moisture storage is not present. The model is especially applicable for short term (maximum a week) moisture storage where the net MAD rates are equal or close to zero. If the model is used to simulate long term moisture storage than the results will be erroneous.

Final Governing Equations

MAC is defined by functional relationship. In the case of mechanical cooling and dehumidification, the amount of latent and sensible cooling performed by the equipment is a function of the outdoor dry-bulb, indoor dry-bulb and indoor wet-bulb temperatures. Mechanical performance characteristics can normally be obtained from manufacturer's data. Generally the equipment performance data are given in tabular format. Therefore, the data usually have to be curve fitted for functional relations that can be used in Equation 1. In air conditioning modeling the amount of moisture removed by the cooling equipment can be represented by the following equation:

$$MAC = LC1 + LC2 \ W_r \qquad (21a)$$

where

$$LC1 = f(TD_o, TD_r) \text{ and } LC2 = f(TD_o, TD_r) \qquad (21b)$$

In Equations 21, LC1 and LC2 denote the machine latent load performance functions. Consequently, Equations 1 through 9 and Equations 14 through 17 with Equations 21 combined with the initial boundary conditions constitute a system of differential equations that describe the moisture balance in a zone. The initial boundary conditions for the system are;

$$\text{at } t = 0 \qquad Wr_i = Wro_i \qquad (22a)$$
$$\text{at } t = 0 \qquad Mce_{i,k} = Mceo_{i,k} \qquad (22b)$$

and

$$\text{at } t = 0 \qquad Mcf_{i,k} = Mcfo_{i,k} \qquad (22c)$$

By substituting Equations 2 through 7 and Equation 21 into Equation 1, substituting Equations 14 through 17 into Equations 8 and 9 and rearranging the terms, the following set of differential equations can be obtained:

$$m_i \ dWr_i/dt = CON1_i + CON2_i \ Wr_i + CON3_{i,j} \ Wr_j - \sum_{k=1}^{nze} dMce_{i,k}/dt - \sum_{k=1}^{nzf} dMcf_{i,k}/dt \qquad (23)$$

$$dMce_{i,k}/dt = hme_{i,k} \ Ame_{i,k} \ (Wr_i - A1e_{i,k} \ Uee_{i,k} - A2e_{i,k}) \qquad (24)$$

$$dMcf_{i,k}/dt = hmf_{i,k} \ Amf_{i,k} \ (Wr_i - A1f_{i,k} \ Uef_{i,k} - A2f_{i,k}) \qquad (25)$$

where

$$CON1_i = MGR_i - \sum_{k=1}^{nzm} LC1_{i,k} + \sum_{k=1}^{nzm} hmL_{i,k} Acp_{i,k} (Wsa_{i,k} - Wsu_{i,k})$$

$$+EACH_i\ m_i\ Wa + IVACH_i\ m_i\ Wa - \sum_{k=1}^{nzc} hc_{i,k} Ac_{i,k} Wc_{i,k} \tag{26a}$$

$$CON2_i = -\sum_{k=1}^{nzm} LC2_{i,k} - IACH_i\ m_i - EVACH_i\ m_i - \sum_{\substack{j=1 \\ j\neq i}}^{nz} EMACH_{i,j}\ m_i - \sum_{k=1}^{nzc} hc_{i,k}\ Ac_{i,k} \tag{26b}$$

$$CON3_{i,j} = \sum_{\substack{j=1 \\ j\neq i}}^{nz} IMACH_{i,j}\ m_j \tag{26c}$$

and

$$CON3_{i,j} = CON3_{j,i} \tag{26d}$$

Finally, Equations 23 through 26, with the initial boundary conditions given by Equations 22, completely define the problem. The solution procedure of the above equations is explained in Appendix A. This procedure has been implemented into the NBS developed TARP program (Walton 1983). The new FSEC enhanced TARP is still in the research stage and is called MADTARP (Moisture Absorption and Desorption Thermal Analysis Program).

RESULTS

The above described algorithm is validated with the field data that have been obtained from the attic of a multifamily living unit located in Oriville, CA, monitored by Lawrence Berkeley Laboratory (Cleary 1984). The monitoring effort by LBL was accurate and detailed to the point that even infiltration/ventilation rates are well described. Good agreement with measured moisture data would not be possible otherwise. The effective mass transfer coefficient (hm) is strongly related to surface boundary layer velocities and very accurate results are only possible when fluid flow parameters can be accurately estimated. The primary attic material (wood) also has well-defined moisture and thermal transfer characteristics. Therefore, the results depicted in Figure 5 are excellent.

In the moisture balance equations described above, the MAD have to be evaluated for each envelope material and furnishings. However, very little MAD data exist for building materials. Therefore, for the following analysis, only two representative building materials (gypsum drywall to represent wall materials and rag felt to simulate furnishings, clothing, linens, rugs, etc.) are used.

A two-story townhouse in Cocoa, FL, is being monitored by FSEC. The monitoring system was designed to collect as much moisture data as practicable. Dry-bulb and dew-point temperatures are measured on both sides of the air conditioner evaporator coil (return air and supply air) and the coil condensate is measured through a calibrated rain guage. Coil measurements are taken only when the condensing unit and evaporator coil blower are operating. Total machine run times are recorded at 15-minute intervals and power consumption of compressors and blowers are recorded through automated kWh pulse counters. Room-dry bulb and wet-bulb or RH measurements are taken both upstairs and downstairs in the townhouse. A full set of site meteorological data are also taken. All data are scanned at 10-second intervals and the average is recorded at 15-minute time increments.

A data set from September 14-15 1984, was chosen for the analysis presented here. During this period the building was ventilated on the nights of September 21-22 and September 22-23 and the air conditioner ran the remainder of the time.

No continuous infiltration measurements were taken on the townhouse due to the expense of such monitoring devices. Therefore, the INF term in Equation 1 is not precisely known. Two sets of one-time infiltration measurements using SF_6 gas chromatograph techniques were performed on September 21. The resulting air change rates were between 0.25 and 0.4 ACH (air changes per hour). Two separate mechanical system air volume flow rate measurements have also been made.

Given the volumetric airflow rate of the machine and the measured dew-point temperature difference across the evaporator coil, the machine's latent performance characteristics may be determined. The volumetric airflow rate of the system was measured by the airflow measuring devices to be between 980 and 1005 CFM (27.75 - 28.46 m^3/min).

In order to validate the algorithm, it is necessary to know all but one of the values on the right-hand side of Equation 1. EMAD+FMAD are the two terms of interest, but INF is not continuously measured, so some accurate estimation of INF must be made. To do this, a reasonable estimate of the effective MAD surface area was assumed and an hourly infiltration schedule was determined through back substitution in Equation 1 using the first day's (September 14, 1985) measured data. This infiltration rate was found to vary between 0.25 and 0.40. The pattern of the variation in infiltration was found to correspond well with the measured environmental wind speeds with the lower ACH at night when wind speed was low. Examination of external wind speeds showed very similar wind speed patterns for the entire period of the data set. Thus, the ACH schedule calculated for the first day was assumed reasonable for the entire period.

Next a set of analysis was performed using this calculated hourly INF schedule to determine the optimum effective MAD surface area (Am) for use in Equations 24 through 26. This optimization was accomplished using the calculated ACH schedule from the first day for all 12 days of the data set. Upon optimization, the most effective MAD surface area was found to be 2798 ft^2 (260 m^2). Figure 6 shows the measured and calculated room humidity ratio for the entire period using this effective MAD surface area.

Next the analysis was performed with the effective MAD surface area set equal to zero to examine results when no MAD is simulated. Results are given in Figure 7 as the error in predicted room humidity ratio with respect to the measured data. Further explanations in the probable penalties in not modelling MAD are discussed in Fairey, Keretecioglu, et al. (1985).

Further informations in the data collection, reduction procedures, adaptation of these algorithms to TARP interactions with mechanical cooling systems and a variety of MADTARP runs can be found in Fairey, Kerestecioglu, et al. (1985).

CONCLUSION

Although moisture transport is still under intensive investigation at FSEC and other institutions, a number of general conclusions may be drawn from this study.

First, the model appears to be highly accurate for predicting moisture transport when the necessary material moisture parameters and building characteristics are known.

The major problem area is the lack of material property data. Extensive literature surveys indicate that moisture data are primarily limited to food products and are unknown for many common building materials. It should also be pointed out that many of the parameters given in the literature are not directly applicable to MAD analysis. Extensive experimental research is needed to establish the described moisture transport parameters for a wide range of common building materials. Besides moisture properties, evaluation of the convective mass transfer coefficient is also very important since moisture transport from surfaces of solid bodies is dominated by convective fluxes.

With the methods described, the MAD rates of envelope walls, furnishings, and internal masses may be calculated. However, the MAD rates of furnishings and some other common materials may be reliably determined only from controlled moisture experiments.

The model presented here does not address long term moisture storage problems. However, for short term moisture storage problems, especially when the net MAD rates are close to each other, then the model can be applied.

The use of this model for hourly building simulation programs still appears very promising. Future moisture modeling research at FSEC will concentrate on the potential development of moisture transfer functions that relate moisture diffusion and MAD to varying temperature and convective mass transfer regimes.

NOMENCLATURE

Ac = Condensation area $(ft^2)-(m^2)$
Acp = Lumped area of cooling coils and condensate pan $(ft^2)-(m^2)$
Ame = Envelope wall moisture absorption and desorption area $(ft^2)-(m^2)$
Amf = Furniture or internal mass moisture adsorption or desorption area $(ft^2)-(m^2)$
A1e, A2e = Envelope adsorption and desorption linearization coefficients
A1f, A2f = Furniture and internal mass adsorption and desorption linearization coefficients
BP = Barometric pressure (kPa)
CON = Amount of surface condensation $(lb_W)-(kg_W)$
CON1,2,3 = Constants used in Equation 26
Cp = Specific heat of air $(Btu/lb_D.F)-(J/kg_D.^{o}C)$
EACH = Exfiltration rate (1/h)
EMACH = Rate of air leaving the zone by internal air flows (1/h)
EMAD = Amount of moisture adsorbed or desorbed by the envelope walls $(lb_W)-(kg_W)$
EVACH = Rate of air leaving the zone by ventilation (1/h)
FMAD = Amount of moisture absorbed or desorbed by the furniture and internal mass $(lb_W)-(kg_W)$
hc = Convective condensation coefficient $(lb_D/h.ft^2)-(kg_D/h.m^2)$
hme = Convective mass transfer coefficient for the envelope $(lb_D/h.ft^2)-(kg_D/h.m^2)$
hmf = Convective mass transfer coefficient for the furniture and internal mass $(lb_D/h.ft^2)-(kg_D/h.m^2)$
hmL = Lumped convective mass transfer coefficient over the cooling coil and condensate pan $(lb_D/h.ft^2)-(kg_D/h.m^2)$
h_T = Convective heat transfer coefficient $(Btu/h.ft^2.F)-(W/m^2.^{o}C)$
IACH = Infiltration rate (1/h)
IMACH = Rate of air coming to the zone by internal air flows (1/h)
INF = Amount of moisture brought or removed by infiltration $(lb_W)-(kg_W)$
IVACH = Rate of air coming to the zone by ventilation (1/h)
LC1, LC2 = Machine latent load removal performance functions
Lde = Effective MAD layer thickness of the envelope walls (ft)-(m)
Ldf = Effective MAD layer thickness of the furnishings and internal mass (ft)-(m)
m = Dry weight of the zone air $(lb_D)-(kg_D)$
MAC = Amount of moisture brought or removed by mechanical systems $(lb_W)-(kg_W)$
Mce = Moisture stored in the envelope walls $(lb_W)-(kg_W)$
Mcf = Moisture stored in the furnishings and internal mass $(lb_W)-(kg_W)$
Mceo = Initial moisture in the envelope materials $(lb_W)-(kg_W)$
Mcfo = Initial moisture in the furnishings and internal mass $(lb_W)-(kg_W)$
Mde = Effective dry weight of the envelope wall material $(lb_D)-(kg_D)$
Mdf = Effective dry weight of the internal furnishings and mass $(lb_D)-(kg_D)$
MIX = Amount of moisture brought or removed by intrazonal infiltration $(lb_W)-(kg_W)$
MGR = Amount of moisture generated within the zone $(lb_W)-(kg_W)$
nz = Number of simulated zones
nzc = Number of possible condensation surfaces within a zone
nze = Number of moisture absorption or desorption envelope walls within a zone
nzf = Number of moisture absorbing or desorbing furnitures and internal mass
nzm = Number of mechanical moisture removing or generating systems within a zone
REV = Amount of moisture reevaporated from cooling coils and condensate pans $(lb_W)-(kg_W)$
RH = Relative humidity
t = time (h)
TD = Dry-bulb temperature $(F)-(^{o}C)$
TW = Wet-bulb temperature $(F)-(^{o}C)$
Ue = Equilibrium moisture content $(lb_W/lb_D)-(kg_W/kg_D)$

Uee = Equilibrium moisture content of the envelope materials $(lb_w/lb_D)-(kg_w/kg_D)$

Uef = Equilibrium moisture content of the furnishings and internal mass $(lb_w/lb_D)-(kg_w/kg_D)$

VEN = Amount of moisture brought or removed by ventilation $(lb_w)-(kg_w)$

Wa = Ambient humidity ratio $(lb_w/lb_D)-(kg_w/kg_D)$

Wc = Humidity ratio of the air evaluated at condensation surface conditions $(lb_w/lb_D)-(kg_w/kg_D)$

Wr = Zone humidity ratio $(lb_w/lb_D)-(kg_w/kg_D)$

Wro = Initial zone humidity ratio $(lb_w/lb_D)-(kg_w/kg_D)$

Wsa = Saturation humidity ratio of the air $(lb_w/lb_D)-(kg_w/kg_D)$

Wse = Surface humidity ratio of the envelope wall $(lb_w/lb_D)-(kg_w/kg_D)$

Wsf = Surface humidity ratio of the furnishings and internal mass $(lb_w/lb_D)-(kg_w/kg_D)$

Wsu = Humidity ratio of mechanical cooling unit supply air $(lb_w/lb_D)-(kg_w/kg_D)$

ρ = Density $(lb_D/ft^3)-(kg_D/m^3)$

Subscripts and Summation Indexes

D = Dry weight
i = Zone or control volume under simulation
j = Adjacent or connected zone to the zone under simulation
k = Different components in the simulation zone
o = Outdoor (ambient) conditions
r = Indoor (simulated zone) conditions
w = Water

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ACKNOWLEDGMENTS

A portion of the work reported here was funded under GRI contract #5082-243-0727 with the Gas Research Institute, 8600 West Bryn Mawr Ave., Chicago, Illinois. The authors thank Douglas Kosar, GRI program manager, for his continued support of this research.

APPENDIX A

In the preceeding sections the governing equations were described, and in this section the solutions to the equations will be given. Substituting Equations 15, 17, and 19 into Equations 24 and 25 and rearranging the terms, the following equations can be obtained:

$$dMce_{i,k}/dt = CON4_{i,k}\, Wr_i + CON5_{i,k}\, Mce_{i,k} + CON6_{i,k} \qquad \text{(A-1)}$$

$$dMcf_{i,k}/dt = CON7_{i,k}\, Wr_i + CON8_{i,k}\, Mcf_{i,k} + CON9_{i,k} \qquad \text{(A-2)}$$

where

$$\begin{aligned} CON4_{i,k} &= hme_{i,k}\, Ame_{i,k} \\ CON5_{i,k} &= hme_{i,k}\, Ale_{i,k}/(\rho_{i,k} Lde_{i,k}) \\ CON6_{i,k} &= hme_{i,k}\, Ame_{i,k}\, A2e_{i,k} \\ CON7_{i,k} &= hmf_{i,k}\, Amf_{i,k} \\ CON8_{i,k} &= hmf_{i,k}\, Alf_{i,k}/(\rho_{i,k} Ldf_{i,k}) \\ CON9_{i,k} &= hmf_{i,k}\, Amf_{i,k}\, A2f_{i,k} \end{aligned} \qquad \text{(A-3)}$$

In Equations A-1 through A-3, i and k represent the zone and the MAD material, respectively. Using the finite difference method, Equations A-1 and A-2 for all MAD materials and zones can be written as follows:

$$Mce^{t+1}_{1,1} = (Mce^{t}_{1,1}/dt+CON4_{1,1}Wr^{t+1}_{1}+CON6_{1,1})/(1/dt-CON5_{1,1})$$

$$Mcf^{t+1}_{1,1} = (Mcf^{t}_{1,1}/dt+CON7_{1,1}Wr^{t+1}_{1}+CON9_{1,1})/(1/dt-CON8_{1,1})$$

.
.
.

$$Mce^{t+1}_{1,nze}=(Mce^{t}_{1,nze}/dt+CON4_{1,nze}Wr^{t+1}_{1}+CON6_{1,nze})/(1/dt-CON5_{1,nze})$$

$$Mcf^{t+1}_{1,nzf}=(Mcf^{t}_{1,nzf}/dt+CON7_{1,nzf}Wr^{t+1}_{1}+CON9_{1,nzf})/(1/dt-CON8_{1,nzf}) \qquad \text{(A-4)}$$

.
.
.

$$Mce^{t+1}_{nz,nze}=(Mce^{t}_{nz,nze}/dt+CON4_{nz,nze}Wr^{t+1}_{nz}+CON6_{nz,nze})/(1/dt-CON5_{nz,nze})$$

$$Mcf^{t+1}_{nz,nzf}=(Mcf^{t}_{nz,nzf}/dt+CON7_{nz,nzf}Wr^{t+1}_{nz}+CON9_{nz,nzf})/(1/dt-CON8_{nz,nzf})$$

Equation 23 in finite difference form would be

$$
\begin{bmatrix}
(m_1/dt-CON2_1) & (-CON3_{1,2}) \ldots & (-CON3_{1,nz}) \\
(-CON3_{2,1}) & (m_2/dt-CON2_2) \ldots & (-CON3_{2,nz}) \\
\vdots & \vdots & \vdots \\
(-CON3_{nz,1}) & (-CON3_{nz,2}) \ldots & (m_{nz}/dt-CON2_{nz})
\end{bmatrix}
\begin{bmatrix}
Wr_1^{t+1} \\
Wr_2^{t+1} \\
\vdots \\
Wr_{nz}^{t+1}
\end{bmatrix}
=
\begin{bmatrix}
m_1/dt\ Wr_1^{t}+CON1_1-ABDES_1 \\
m_2/dt\ Wr_2^{t}+CON1_2-ABDES_1 \\
\vdots \\
m_{nz}/dt\ Wr_{nz}^{t}+CON1_{nz}-ABDES_{nz}
\end{bmatrix}
\quad (A\text{-}5)
$$

where

$$
ABDES_i = \sum_{k=1}^{nze} (Mce_{i,k}^{t+1}-Mce_{i,k}^{t})+\sum_{k=1}^{nzf} (Mcf_{i,k}^{t+1}-Mcf_{i,k}^{t}) \quad (A\text{-}6)
$$

In the above equations, dt denotes the time step, and superscripts t+1 and t denote the present and previous time steps, respectively. The solution procedure is summarized below.

Initially the humidity ratios for each zone have to be guessed. With the guessed humidity ratios, Equation A-4 can be solved in order to predict the moisture content of the envelope and furnishings at the end of the time step. Since the initial moisture content of the materials will be known either from the initial boundary conditions or previous calculations, Equation A-6 can be solved for the total MAD of the zone. Finally, Equation A-5 can be solved to predict the zone humidity ratios. If the guessed and predicted zone humidity ratios are not within an acceptable error tolerance, the whole procedure has to be reexecuted. Figure A-1 illustrates the steps that have to be followed in the solution procedure in order to solve the described equations.

At the end of the fifth step, if convergence is not achieved, the calculated indoor humidity ratios have to be relaxed before repeating the procedure. Underrelaxing the indoor humidity ratios substantially enhances the convergence.

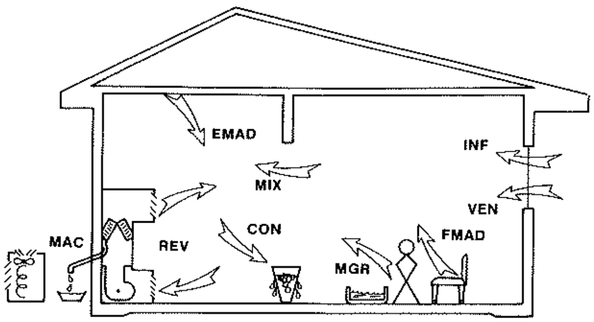

Figure 1. Schematic showing principle components of room moisture balance

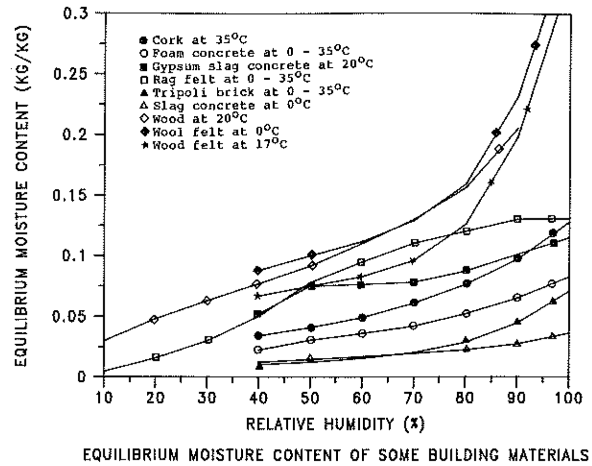

Figure 2. Equilibrium moisture content of building materials (Luikov 1965)

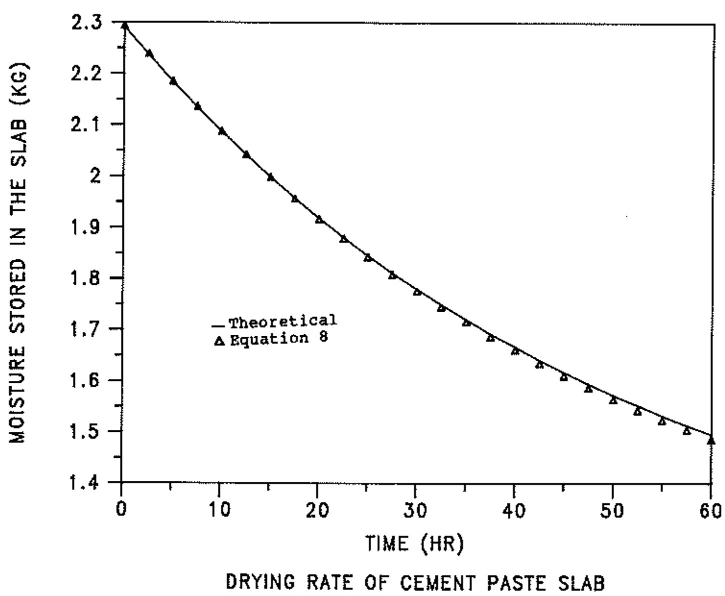

Figure 3. Drying rate of cement paste slab

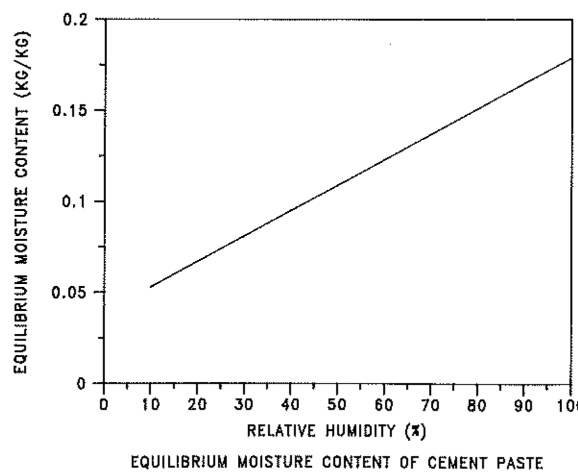

Figure 4. Equilibrium moisture content of cement paste (Huang 1979)

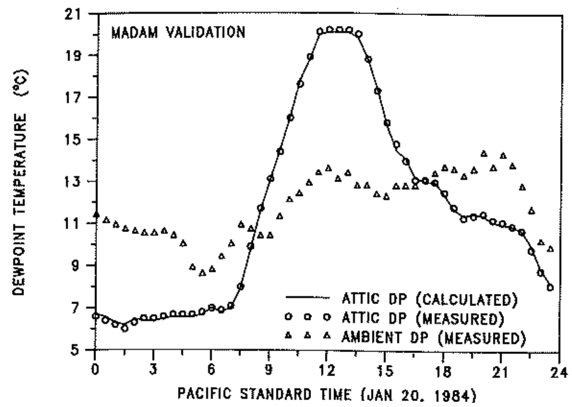

Figure 5. Measured ambient air and attic air dew point compared with algorithm prediction of attic air dew point for residence in Oroville, CA (Cleary 1984)

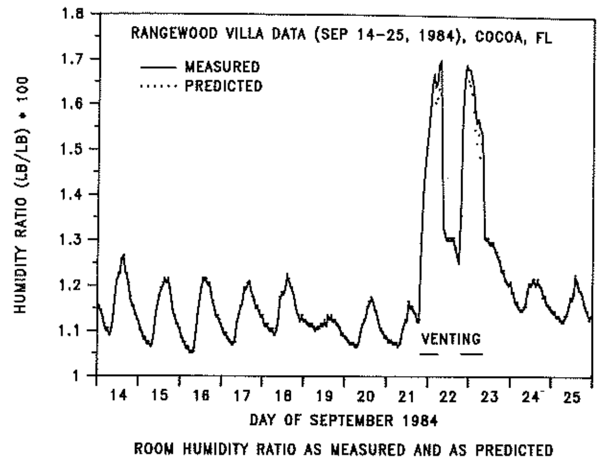

Figure 6. Measured and predicted ratios for room humidity

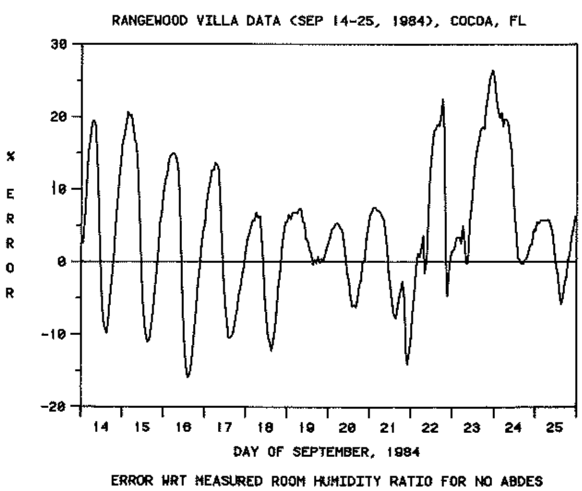

Figure 7. Error with respect to measured room humidity ratio without MAD

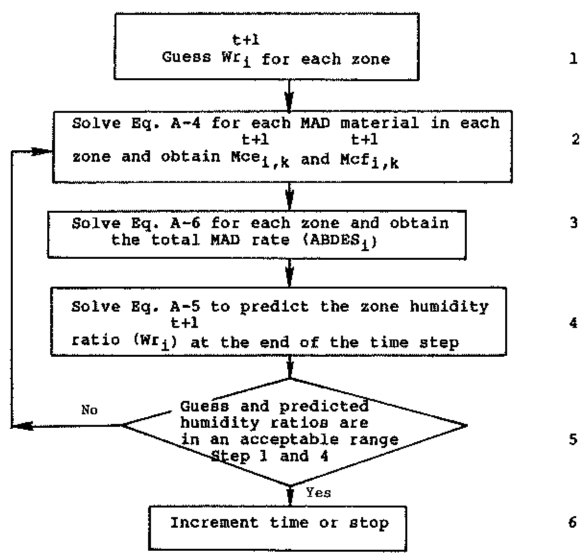

Figure A-1. Solution procedure of equations