Evaluation of the Effective Moisture Penetration Depth Model for Estimating Moisture Buffering in Buildings

J. Woods, J. Winkler, and D. Christensen
National Renewable Energy Laboratory

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Nomenclature

A	surface area (m^2)
c_p	specific heat (J kg^{-1} K^{-1})
D_{12}	moisture diffusivity, $D_{12} = \delta_{perm}RT$ (m^2 s^{-1})
d_{EMPD}	effective moisture penetration depth of surface layer (m)
$d_{EMPD\text{-}deep}$	effective moisture penetration depth of deep layer (m)
$du/d\phi$	slope of moisture sorption curve ($\mathrm{kg_{moisture}\ kg_{dry}^{-1}}$)
e_m	moisture effusivity (J m^{-2} K^{-1} s$^{-1/2}$)
e_{th}	thermal effusivity (kg m^{-2} Pa^{-1} s$^{-1/2}$)
h_{fg}	enthalpy of vaporization for water (2500 kJ kg^{-1})
h_{m}	boundary layer mass transfer coefficient (check)
k	thermal conductivity (W m^{-1} K^{-1})
L	material thickness (m)
$\dot{m}_{\mathrm{air,infiltration}}$	mass flow rate of infiltration air (kg s^{-1})
$\dot{m}_v\big\vert_{\mathrm{matl-sorption}}$	moisture sorption rate into building materials (kg s^{-1})
$\dot{m}_v\big\vert_{\mathrm{gain}}$	internal moisture gain (kg s^{-1})
p_{sat}	saturation vapor pressure (Pa)
q_{sorption}	heat transfer from moisture sorption (W)
R	gas constant for water (461.5 J kg^{-1} K^{-1})
T	temperature (°C)
t	time (s)
u	moisture capacitance ($\mathrm{kg_{moisture}\ kg_{dry}^{-1}}$)
V	volume (m^3)
x	distance into wall (m)

δ_{perm}	vapor permeability (kg m^{-1} s^{-1} Pa^{-1})
ρ_{air}	air density (kg m^{-3})
ρ_{dry}	dry material density (kg m^{-3})
ϕ	relative humidity
ϕ_{matl}	effective relative humidity of material
τ_{p}	humidity load cycle period (s)
Ψ	$\mathrm{EMPD}_1^{v7.1}$ model correlating parameter; Eq. (A.3) (kg_{vapor} K m^2 J^{-2} $s^{-1/2}$)
ω	humidity ratio ($\mathrm{kg}_{\mathrm{vapor}}\ \mathrm{kg}_{\mathrm{air}}^{-1}$)
ω_f	angular frequency for sinusoidal-varying humidity (rad s^{-1})

subscripts

air	property of air
amb	ambient condition
zone	building zone

Executive Summary

Building materials and furnishings play an important role in moderating relative humidity fluctuations. Accurately accounting for moisture buffering in building simulations is central in determining the need for, and the energy use from, controlling humidity. In building modeling, moisture buffering has typically either been ignored or has been lumped with the zone air using an effective moisture capacitance multiplier. Researchers have also used finite-difference models to simulate moisture transfer within materials, which are more physically realistic than the effective capacitance model, but require orders of magnitude more computation time.

This study examines the effective moisture penetration depth (EMPD) model and its suitability for building simulations. The EMPD model is a compromise between the simple, inaccurate, effective capacitance approach and the complex, yet accurate, finite-difference approach. Two formulations of the EMPD model were examined, including the model used in the EnergyPlus building simulation software. We uncovered an error in the EMPD model in EnergyPlus, which was fixed with the release of EnergyPlus version 7.2. The EMPD model in earlier versions of EnergyPlus should not be used.

Three simple building simulation cases were used to compare the two EMPD formulations, the effective capacitance model, and the finite-difference model. An analytical solution for the first case showed that the two EMPD formulations were not equal, but that both were improvements over the effective capacitance model. For the cases that more closely resemble real building loads, the improvement of the EMPD model over the effective capacitance model was small unless the EMPD model included two penetration depths: a surface layer for short-term humidity fluctuations, and a deep layer for longer term fluctuations. We are presently working to implement the dual-depth EMPD model in a future EnergyPlus version.

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1 Introduction

Building simulation software can be used to predict a building's latent and sensible loads, and the resulting energy use, to maintain temperature and humidity set points. As building codes have tightened in recent years, insulation improvements have resulted in reduced sensible load. The latent load from internal gains and required ventilation has remained relatively constant. This has increased the need for dehumidification equipment and for accurately predicting the space relative humidity [1, 2].

Indoor relative humidity should be controlled to maintain occupant health and comfort, and to limit the likelihood of building decay such as mold growth. The humidity in a building is primarily affected by five factors: internal moisture gains, ventilation, infiltration, removal with space-conditioning equipment, and moisture sorption into (or desorption out of) the materials. Building models often neglect this last term, but it is becoming more important because of the need for better humidity control and prediction. Many building simulation programs use an effective capacitance (EC) model, which uses a moisture capacitance multiplier to combine this term with the zone air [3]. This model is an improvement over neglecting the moisture buffering of the materials entirely. However, it does not appropriately model the physics of moisture transfer into materials, and the multiplier is empirical and difficult to estimate for different wall types and furnishings. Researchers have also used finite-difference models to simulate moisture transfer within materials [4-6]. Although these finite difference models are more realistic, they require orders of magnitude more computation time than the effective capacitance method.

There is a need for simpler moisture prediction models with fast solution times and reasonable accuracy. Faster solving time enables optimization and large parametric studies to compare several options for the building envelope and space conditioning equipment. One possibility is the effective moisture penetration depth (EMPD) model, which was developed independently by Cunningham [7, 8] and Kerestecioglu et al. [9] in the late 1980s. The EMPD model is derived by assuming cyclic variations in the zone humidity, and therefore in the humidity loads. This is generally a reasonable assumption for hypothetical internal latent gains, which occur predictably on a daily basis, but is less certain for latent loads from infiltration and ventilation. Two formulations of the EMPD model have emerged.

One model [10] is currently a user-selectable option in the EnergyPlus building simulation software [11]. This non-isothermal formulation (referred to here as EMPD_1) is coupled with conduction transfer functions for the energy equations. Although this model has been used in EnergyPlus for various building simulations, there has yet to be a verification study of it. This research revealed that the implementation of the EMPD equations in EnergyPlus version 7.1 (and prior versions) was incorrect. This study discusses problems with this implementation (referred to as $\text{EMPD}_1^{v7.1}$) and assesses its accuracy. We modified the EnergyPlus source code to correct these problems. The fixed EMPD_1 model, available starting in EnergyPlus version 7.2, is used in this report.

There is also a different formulation of the EMPD model (referred to here as EMPD_2) that is a user-selectable option for the building model in the TRNSYS software. It typically includes two effective depths: a surface layer to account for short-term transients and a deep layer to represent materials' response to longer term moisture events such as seasonal changes [12]. In contrast to

EMPD_1, it is an isothermal model. The building models using the EMPD_2 formulation, such as TRNSYS, include energy balance equations, but they neglect the effects of temperature on the equilibrium moisture content of the materials. They also typically neglect the latent heat resulting from water sorption and desorption. Several researchers have verified the EMPD_2 approach [13-15], but for limited cases. Woloszyn et al. [16] performed a more in-depth study using the EMPD_2 approach in TRNSYS. They focused on a ventilation system that was controlled based on relative humidity, but also reported good agreement between the humidity predictions from the EMPD_2 model and measured humidity data from a test room.

The purpose of this study is to evaluate both formulations of the EMPD model by comparing them with the simple EC model and a detailed finite-difference model (referred to here, as in EnergyPlus, as the combined heat and moisture transfer (HAMT) model [5]). All four models (EC, EMPD_1, EMPD_2, and HAMT) are simulated for three separate cases, each with a periodic, internal latent gain and continuous ventilation. The ambient (outdoor) humidity is different for each case: (1) constant ambient humidity, (2) sinusoidal-varying ambient humidity, and (3) ambient humidity from weather data. These cases are used to assess the “accuracy” of the two EMPD model formulations compared to an analytical solution, compared to the common EC model, and compared to the more robust HAMT model. Thus, this study covers two of the three verification and validation schemes in ASHRAE Standard 140 [17]: analytical verification and comparative testing. These cases help the National Renewable Energy Laboratory (NREL) reach its goals to improve the accuracy of building energy simulations [18], similar to other evaluations performed by NREL [19, 20]. The goal in this study is not to find the “best” model, but rather to compare the dynamics of each model for simple cases, and gain insight into these models and their use in building energy simulations.

2 Methods

The four moisture storage and transport models compared in this study are listed in Table 1. Relatively simple simulations are performed with these models using the rectangular building in Figure 1. These simulations are used to explore these models' responses to different moisture loads. The equation governing moisture transfer in these simulations is:

$$\rho_{air} V_{zone} \frac{d\omega_{zone}}{dt} = \dot{m}_{\text{air,ventilation}} \left(\omega_{amb} - \omega_{zone}\right) + \dot{m}_v\big|_{\text{gain}} - \dot{m}_v\big|_{\text{matl-sorption}} \tag{1}$$

where the first term is the moisture capacitance of the zone air, the second term the moisture added with ventilation air, the third term the moisture gains, and the final term the moisture sorption into (or desorption out of) the building materials. In these terms, ρ_{air} is the dry-air density of the zone air, V_{zone} the zone volume, ω_{zone} and ω_{amb} the zone and ambient humidity ratios, and t time. Moisture removal with an air conditioner or dehumidifier would typically be a term on the right-hand side of this equation, but this is not considered in this study for simplicity.

The time step (*dt*) for the simulations was 6 minutes for each model. Although the HAMT model generally needs a smaller time step than the other models, we found that all of the models were insensitive to the time step for time steps 6 minutes or shorter. The original EMPD_1 formulation was strongly affected by the time step (see Figure A.2 in the Appendix), but once fixed the simulation results for 6-minute and 15-minute time steps were nearly the same.

The four models solve for the last term in Eq. (1), which is the focus of this study. Sections 2.1 through 2.3 describe how each of these models calculates this last term.

Table 1. Description of Four Models Analyzed in This Study

Model	Description	Isothermal Assumption?	Used in EnergyPlus?	Simulation Run Time
EC	Effective capacitance; multiplier on room air volume to simulate added moisture capacity due to walls and furnishings.	isothermal	EnergyPlus default	defined as 1
EMPD_1	Effective moisture penetration depth; based on cyclical humidity loads; solves for moisture sorption rate using Eq. (6).	non-isothermal	user selectable option [a]	~1.05
EMPD_2	Similar to EMPD_1, but solves for moisture sorption rate using Eq. (7). Uses two EMPD values (surface and deep).	isothermal	not in EnergyPlus [b]	~1.05
HAMT	Combined heat and moisture transfer. Solves for temperature and moisture content within materials using finite-difference method.	non-isothermal	user selectable option	~10^2-10^4

[a] EMPD_1 is the fixed model in EnergyPlus v7.2. The model in prior versions is referred to as $\text{EMPD}_1^{v7.1}$.
[b] Although the EMPD_2 model is not currently available in EnergyPlus, we made a custom EnergyPlus version for this study that uses the EMPD_2 model.

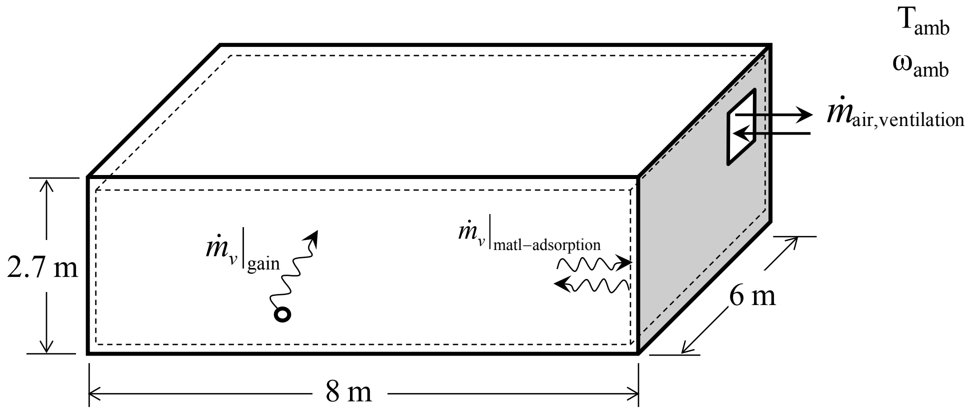

Figure 1. Building for test cases

2.1 Effective Capacitance Model

The EC model does not explicitly solve for the moisture sorption term, but instead lumps its effect in with the moisture capacitance of the zone air:

$$\rho_{air}(\text{EC})V_{zone}\frac{d\omega_{zone}}{dt} = \dot{m}_{\text{air,ventilation}}(\omega_{amb} - \omega_{zone}) + \dot{m}_v|_{\text{gain}} \tag{2}$$

where EC is the effective moisture capacitance of the walls and furnishings. For example, a building with an EC of 15 means the building materials, plus the zone air, can absorb 15 times more moisture than the zone air alone. A 2001 study [3] proposed EC values ranging from 10 to 25 for different zone types (e.g., office vs. library). Values of 15 and 20 have been used in simulations for evaluating HVAC equipment [21, 22].

The EC values are empirical and have little physical connection to reality. The lumping of the room air node with the material nodes implies that the resistance to moisture transfer between the room air and the materials is negligible.

2.2 Finite-Difference Heat and Moisture Transfer Model

The HAMT model in EnergyPlus uses a finite-difference approach, derived from Künzel [5], for solving both heat and mass transfer through the building materials. The detailed moisture equations for the finite-difference equations are not included here, but can be found in the EnergyPlus Engineering Reference [11]. The following equation governs moisture transfer and storage inside the wall:

$$\frac{du}{d\phi}\frac{d\phi}{dt} = \delta_{perm}\frac{d(p_{sat}\phi)}{dx} \tag{3}$$

where δ_{perm} (kg/m-s-Pa) is the vapor permeability, p_{sat} the saturation vapor pressure, u the moisture capacitance of the material (kg/kg), ϕ the relative humidity, and $du/d\phi$ the slope of the moisture capacitance curve. Eq. (3) can be discretized and solved using the finite-difference method.

The HAMT model is the most rigorous of the four models studied and is used here as a benchmark for comparison. It is the basis for the hygrothermal modeling program WUFI, developed by the Fraunhofer Institute for Building Physics, and it is expected to be more physically realistic in modeling moisture transport and storage through building materials than the other models. However, as indicated in Table 1, the simulation run time is several orders of magnitude longer.

In addition to vapor transfer, the HAMT model also calculates liquid transfer, which becomes more important at high moisture contents. In this analysis, we assume that all moisture transport mechanisms (vapor and/or liquid) are adequately modeled using a constant vapor permeability. We set the liquid transport coefficients in EnergyPlus to zero. Although this is not strictly accurate [5], it allows for a straightforward comparison to the EMPD models, which do not use liquid transport coefficients.

2.3 Effective Moisture Penetration Depth Model

The EMPD model is based on the assumption that the moisture transfer takes place between the zone air and a thin fictitious layer of uniform moisture content of thickness d_{EMPD}. This uniform moisture content is a function of the relative humidity, as in the HAMT model. Both EMPD models solve the following equation:

$$\rho_{matl} A d_{EMPD} \frac{du}{dt} = h_m A(\omega_{zone} - \omega) \tag{4}$$

where ρ_{matl} is the bulk, dry density of the adsorbing material, d_{EMPD} the effective moisture penetration depth, A the surface area, h_m the airside convective mass transfer coefficient (kg/m^2-s), and ω the humidity ratio of air in equilibrium with the material.

The first method (EMPD$_1$), used in EnergyPlus, transforms the time derivative of the moisture content into [10, 11]:

$$\frac{du}{dt} = \frac{\partial u}{\partial \omega}\frac{d\omega}{dt} + \frac{\partial u}{\partial T}\frac{dT}{dt} \tag{5}$$

where $\partial u/\partial \omega$ and $\partial u/\partial T$ are calculated from the moisture sorption curve ($u = f(\phi)$) and from the relationship between relative humidity and temperature. The non-isothermal term, which includes the temperature derivative (dT/dt), is calculated from the temperature change between the previous time step and the current time step. Substituting Eq. (5) into Eq. (4) creates an ordinary differential equation that can be solved for ω:

$$\rho_{matl} A d_{EMPD} \left(\frac{\partial u}{\partial \omega}\right)\frac{d\omega}{dt} = h_m A(\omega_{zone} - \omega) + \rho_{dry} A d_{EMPD} \left(\frac{\partial u}{\partial T}\right)\frac{dT}{dt} \tag{6}$$

The second method (EMPD$_2$), used in TRNSYS, is an isothermal model; it does not include the effects of temperature. Although there are some variations [13, 14, 23], all calculate moisture transfer into wall materials with an equation similar to:

$$\rho_{matl} A d_{EMPD} \frac{du}{d\phi_{matl}} \frac{d\phi_{matl}}{dt} = \frac{A\left(\omega_{zone} - \omega\right)}{\frac{1}{h_m} + \frac{d_{EMPD}}{2 p_{air} \delta_{perm}}} + \frac{A\left(\omega_{deep} - \omega\right)}{\frac{d_{EMPD}}{2 p_{air} \delta_{perm}} + \frac{d_{EMPD-deep}}{2 p_{air} \delta_{perm}}} . \tag{7}$$

The term on the left side is the moisture accumulation in the material (ϕ_{matl} is the effective relative humidity *in* the material) and the two terms on the right side are the moisture transfer from the zone to the *surface layer* and the moisture transfer from the surface layer to the *deep layer*. The deep layer takes into account the buffering of longer term humidity variations. In the denominators, the $1/h_{\mathrm{m}}$ term is the moisture transfer resistance in the airside boundary layer; the other three terms are the moisture transfer resistances for diffusion into the material. In these three terms, the multiplier of 2 places the nodes at the center of the buffer layers.

2.3.1 Effective Moisture Penetration Depth Model Parameter Estimation

The EMPD model is derived based on a cyclic moisture variation, which must be estimated *a priori* to accurately estimate the effective moisture penetration depth, d_{EMPD}. For a perfectly periodic boundary condition at the wall (i.e., periodic cycling of ω_{zone}), the EMPD model will give an exact solution assuming that the sorption curve, $u(\phi)$, is known and the vapor permeability, δ_{perm}, is known and constant. In this case, the d_{EMPD} is:

$$d_{EMPD} = \sqrt{\frac{\delta_{perm} p_{sat} \tau_p}{\rho_{dry} \frac{du}{d\phi} \pi}} \tag{8}$$

where τ_p is the humidity cycle period(s). The moisture sorption curve, $u(\phi)$, can be nonlinear, but d_{EMPD} must be estimated from a linear approximation of this curve ($du/d\phi$).

Eq. (8) is used to estimate d_{EMPD} in the EMPD$_1$ model and both d_{EMPD} and $d_{EMPD\text{-}deep}$ in the EMPD$_2$ model. The surface layer, d_{EMPD}, is based on the short-term fluctuations of humidity, typically on the order of a day. The deep layer, $d_{EMPD\text{-}deep}$, is based on longer term humidity fluctuations, which may be from short-term changes in weather (~weeks) or seasonal variations (~months).

Eq. (8) is the most common method for estimating d_{EMPD}, but the EnergyPlus Engineering Reference mentions a different, empirical equation [10]. This equation is not used in this report, but we found that it typically gives d_{EMPD} values around 50% higher than those estimated with Eq. (8). Although the method used to estimate d_{EMPD} will affect the results in this study, it does not affect the overall conclusions.

2.3.2 Combining the Effective Moisture Penetration Depth Model With Conduction Transfer Functions: Correcting the Formulation in EnergyPlus v7.1

With the simplified EMPD model equations above, EnergyPlus uses conduction transfer functions [24, 25] to model heat transport and storage in the building materials. The details of these calculations can be found in the EnergyPlus Engineering Reference [11]. The relevant equations for this discussion are related to the temperature calculation for the wall interior surface. This is where the latent heat from moisture sorption is released or absorbed, and this temperature also affects the equilibrium moisture content at the wall surface.

The inside surface temperature is calculated iteratively with damping coefficients to ensure convergence. In EnergyPlus v7.1 and earlier versions, the inside surface temperature was first calculated without considering the latent heat released or adsorbed at the surface. The moisture transfer was then calculated using Eq. (5), with the surface temperature derivative term (*dT/dt*) based on the newly calculated surface temperature and the previous time step surface temperature. The heat of sorption was then calculated with:

$$q_{\text{sorption}} = \dot{m}_v\big|_{\text{matl-sorption}} h_{fg} \tag{9}$$

where h_{fg} is the heat of vaporization of water. Next, the surface temperature was recalculated with this additional sorption heat transfer. The problem with the $\text{EMPD}_1^{\text{v7.1}}$ model was the order in which these equations were evaluated. The *dT/dt* term was initially calculated incorrectly, as it did not consider the adsorption heat. Multiple iterations of these equations compounded the problem and resulted in substantial inaccuracy.

In the modified EnergyPlus implementation (EMPD_1), Eq. (9) is solved before the surface temperature is calculated. During the first iteration, the *dT/dt* term is zero, but the following iterations use the correct *dT*; one that includes the effect from the sorption heat.

2.4 Building Simulation Test Cases

The roof, floor, and walls of the building used for the test cases (Figure 1) are made of concrete with material properties given in Table 2. The internal latent gain in all cases is 0.5 kg/h (347 W) from 9:00 to 17:00 and zero at all other times; the ventilation is constant at 0.5 air changes per hour. To avoid effects outside the scope of the moisture buffering in this study, the following simplifications were made:

- The floor is not ground coupled, but is instead exposed to outside air at the exterior surface.
- The air in the zone is assumed to be well mixed.
- The zone has no temperature or humidity control.
- The convective mass transfer coefficient at the interior surface is a constant 2×10^{-8} kg/m^2-s-pa.
- The moisture transfer from the outside air through the exterior surface is zero.
- Solar radiation and radiation exchange with the sky are ignored.
- There is no furniture in the zone.

Table 3 shows that each case uses a different ambient humidity: (1) constant, (2) varying as a sine wave, and (3) varying based on weather data. The ambient temperatures in all three cases are constant. These simulations are not meant to be realistic, but their simplicity gives solutions that are predictable, intuitive, and can be used to evaluate the various modeling frameworks, as in [19, 20]. The results also provide insight into how the models may perform under more complex (realistic) forcing.

Table 2. Properties of Test Material (aerated concrete)

Material Property	Value	Units
Thickness, L	0.05	m
Density, ρ_{dry}	650	kg/m^3
Sorption curve slope, $du/d\phi$	0.0661	kg/kg
(*HAMT*) Permeability, δ_{perm}	3.0E-11	kg/m-s-Pa
(*EMPD*) Penetration depth, d_{EMPD} [a]	0.006706	m
(EC) Moisture capacitance multiplier	15	
Thermal properties for non-isothermal models:		
Specific heat, c_p	800	J/kg-K
Thermal conductivity, k	0.1	W/m-K

[a] d_{EMPD} is calculated based on τ_p = 24 hours.

Table 3. Test Cases

Case	Description	T$_{amb}$ (°C)	ω_{amb} (kg/kg)	$\dot{m}_v\big|_{gain}$ (kg/h)
1	Latent gain with constant ventilation (analytical solution)	20	0.00434	0.5
2	Latent gain with cyclical ambient humidity[a]	28	0.008 + sin(ω_f t)	0.5
3	Latent gain with random ambient humidity	28	weather data	0.5

[a] angular frequency, ω_f, used here is 0.04 rad/hr, which corresponds to a cycle period of 157 hours.

Using τ_p = 24 hours, the penetration depth for the EMPD$_1$ model is 6.7 mm. For the EMPD$_2$ model, the surface layer thickness is also 6.7 mm, and the deep layer thickness is 17 mm based on the 157-hour cycle period. For case 3, the deep layer thickness was estimated based on the time between large humidity fluctuations, which occur on the order of weeks (Figure 2). Using τ_p = 10 days results in a deep layer thickness of 21 mm.

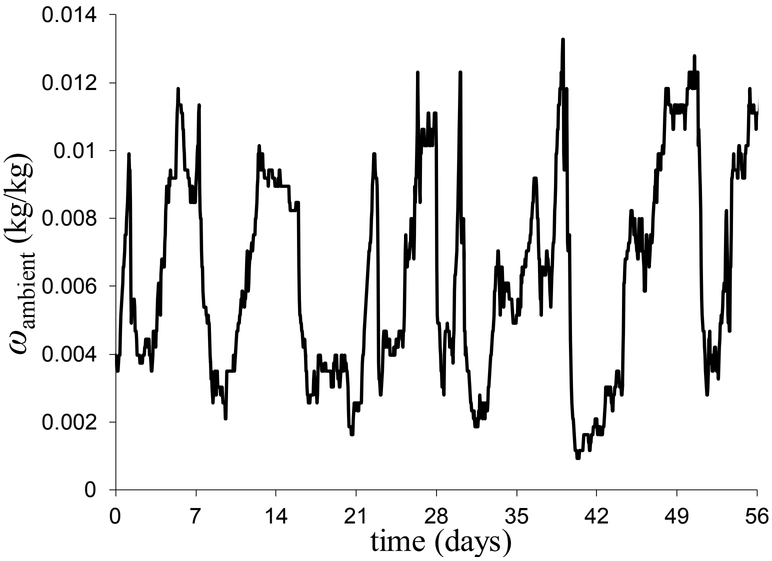

Figure 2. Ambient humidity used for case 3 simulations

3 Results and Discussion

3.1 Case 1: Internal Latent Gain (Isothermal Models)

The simplicity of case 1 enables an analytical solution if isothermal conditions are assumed, as presented by Bednar and Hagentoft [26]. For an equal comparison, the EnergyPlus source code was modified for the $EMPD_1$ and HAMT models to make them isothermal. These are referred to as $EMPD_1$ (isothermal) and HAMT (isothermal). The results from the four models are compared to the analytical solution in Figure 3.

The HAMT and $EMPD_2$ models match the analytical solution reasonably well. The $EMPD_1$ model matches the general trend: a steep increase at the start of the latent gain, followed by a shallower increase shortly after. However, the $EMPD_1$ model predicts a humidity rise[1] (or amplitude) caused by the latent gain that is 27% below the analytical solution; both the HAMT and $EMPD_2$ models predict this humidity rise within 6%. The EC model predicts the humidity rise within 7%, but it misses the dynamics that occur at the wall, with a nearly linear humidity change. In fact, this 7% "error" is somewhat arbitrary, because the choice of EC = 15 is somewhat arbitrary. Using EC = 10 instead results in a humidity rise 38% higher than the analytical solution, showing that the effective capacitance results are sensitive to the chosen multiplier.

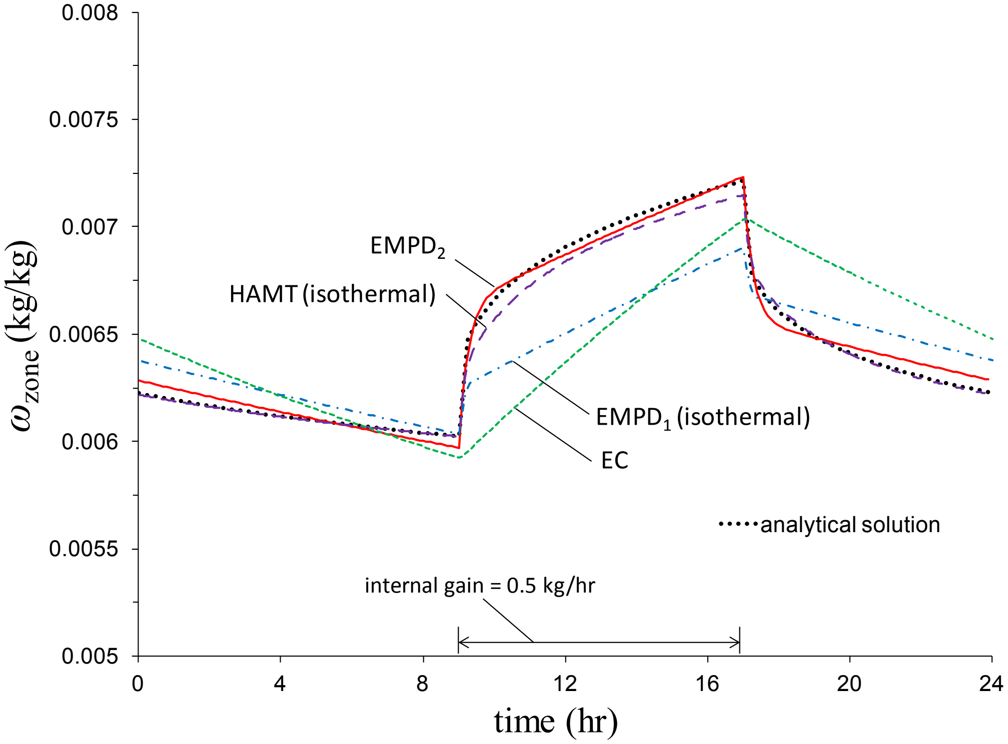

Figure 3. Moisture models compared to an analytical solution. $EMPD_1$ (isothermal) and HAMT (isothermal) models were modified so there is no heat of sorption

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[1] The humidity rise is the difference between the minimum and maximum zone humidity ratios.

The $EMPD_2$ model was simulated with $d_{EMPD\text{-}deep}$ set to zero, but the result would be similar if the deep buffer layer were included. Similar results were found by researchers using the $EMPD_2$ model without a deep-buffer layer [14, 27, 28]. The deep buffer layer is not needed because there is only one cycle period (24 hours) and therefore only one d_{EMPD}.

Therefore, the difference between $EMPD_1$ and $EMPD_2$ for this simple case is *not* due to the additional deep buffer of the $EMPD_2$ formulation, but rather to the differences in the way the EMPD equations are solved (see Section 2.3). The $EMPD_1$ model solves directly for the humidity ratio at the air-material interface (Eq. (6)) and does not include the moisture resistance for diffusion into the material. The $EMPD_2$ model (Eq. (7)) includes this resistance ($d_{EMPD}/(2\rho_{air}\delta_{perm})$, which accounts for the slower moisture transfer, and therefore faster zone humidity change, compared to the $EMPD_1$ model.

The deep buffer layer is used to simulate moisture sorption at longer time scales, as discussed in Section 3.3. Before this, we return to the HAMT and $EMPD_1$ models as they are intended to be: non-isothermal models, which also illustrates the problems with the $EMPD_1^{v7.1}$ model.

3.2 Case 1: Internal Latent Gain (Non-Isothermal Models)

This section repeats case 1 with the non-isothermal models: HAMT and $EMPD_1$. These models are non-isothermal because they include the heat of sorption at the material surface, and they include the dependence of the equilibrium surface moisture content on temperature. We first consider the $EMPD_1$ model in EnergyPlus v7.2, and then compare this to the model used in prior versions ($EMPD_1^{v7.1}$).

To exaggerate the effects from the heat of sorption, we use a thermal conductivity of 0.1 W/m-K for concrete, which is slightly lower than estimates from Kumaran (0.2 to 0.6 W/m-K) [29]. The trend predicted by both models (Figure 4) is in line with expectations; the heat of sorption lowers the zone's minimum humidity and raises its maximum humidity. In other words, the moisture buffering is decreased. The root cause of this decreased moisture buffering is the inverse relationship between temperature and the equilibrium moisture content through the relative humidity. Water vapor absorbs into the material, which releases the heat of sorption and increases the surface temperature. The higher temperature lowers the relative humidity, which decreases the equilibrium moisture content. Therefore, the material absorbs less moisture from the room air.

The added energy at the surface is dissipated through convection into the air and conduction into the material. A lower material thermal conductivity slows the rate of heat dissipation into the wall, which results in higher temperatures and lower moisture buffering. The process is reversed during vapor desorption, where sensible energy must replace the heat of sorption lost at the surface. This low thermal-conductivity case illustrates this effect. The humidity rise predicted with $k = 10$ W/m-K for the $EMPD_1$ and HAMT models are within 2% and 0.5% of the isothermal model, respectively. For $k = 0.1$ W/m-K, these humidity rises are higher than the isothermal model by 12% and 26%, respectively.

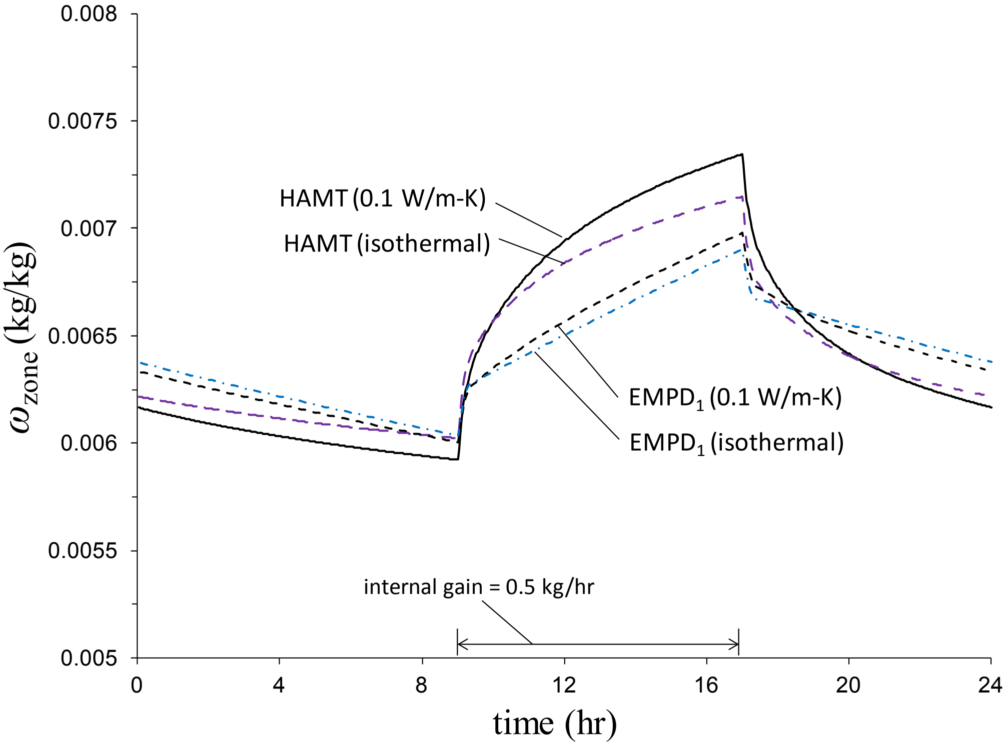

Figure 4. Predicted zone humidity for non-isothermal and isothermal EMPD$_1$ models and non-isothermal and isothermal HAMT models

These results indicate that the difference between isothermal and non-isothermal models depends on the material properties, but it also depends on the zone temperature. If we change the latent gain to a sensible gain, as done in [14], we find another potential problem with isothermal models. For this case, an isothermal model predicts a higher zone temperature, but no change in zone humidity. In a non-isothermal model, the higher zone temperature raises the wall surface temperature, and therefore decreases the equilibrium moisture content of the wall. This causes moisture desorption from the wall into the zone, which increases the zone humidity and moderates the rise in surface temperature. This moderating effect essentially adds thermal capacitance to the building, using moisture as a phase-change material.

This means a non-isothermal model could predict a different ratio of sensible to latent cooling than an isothermal model at different times of the day. It could also mean an air conditioner will stay off (i.e., the temperature will stay below set point) for times where an isothermal model predicts the air conditioner will turn on. The extent of these effects is unclear, and quantifying them is outside of the scope of this study. It is clear, though, that there are many more factors that will influence the humidity response of a modeled space when considering the latent-sensible coupling of moisture sorption.

Because these non-isothermal effects could be important, we need to know how to include these effects in a building simulation. This requires the coupling of the moisture equations with the energy equations. This is not always straightforward, as illustrated by the EMPD$_1^{v7.1}$ model. The differences between the $\text{EMPD}_1^{v7.1}$ equations and the EMPD_1 equations in version 7.2 are discussed in Section 2.3.2.

Figure 5 shows the results from the $\text{EMPD}_1^{v7.1}$ model (using EnergyPlus v7.1) with three different values for the material thermal conductivity. This clearly shows that the $\text{EMPD}_1^{v7.1}$ model is incorrect, at least in some situations. The "fixed" model (EMPD_1) does not show this problem. For k = 0.1 W/m-K, the $\text{EMPD}_1^{v7.1}$ model predicts a humidity below ambient, even though there is no moisture sink in the model. This obviously cannot be the case. The results for k = 1 W/m-K are higher, but still lower than expected and the results for k = 10 W/m-K approach the fixed EMPD_1 model. This problem is related only to the coupling of the moisture equations with the energy equations; the isothermal model of EMPD_1 and $\text{EMPD}_1^{v7.1}$ (shown as *$EMPD_1$ (isothermal)* in Figure 3) are the same.

In the Appendix, we more thoroughly investigate the $\text{EMPD}_1^{v7.1}$ model and assess its accuracy for a range of material properties. We also show that the EMPD_1 model in EnergyPlus v7.2 fixes the problem. This fix is important, because it allows for a non-isothermal EMPD model in EnergyPlus, whether it is the EMPD_1 model, an EMPD_2 model modified to be non-isothermal, or another similar lumped wall moisture model. This issue did not, and does not, affect the HAMT model because that model uses a finite-difference method to solve the energy equations, as opposed to conduction transfer functions.

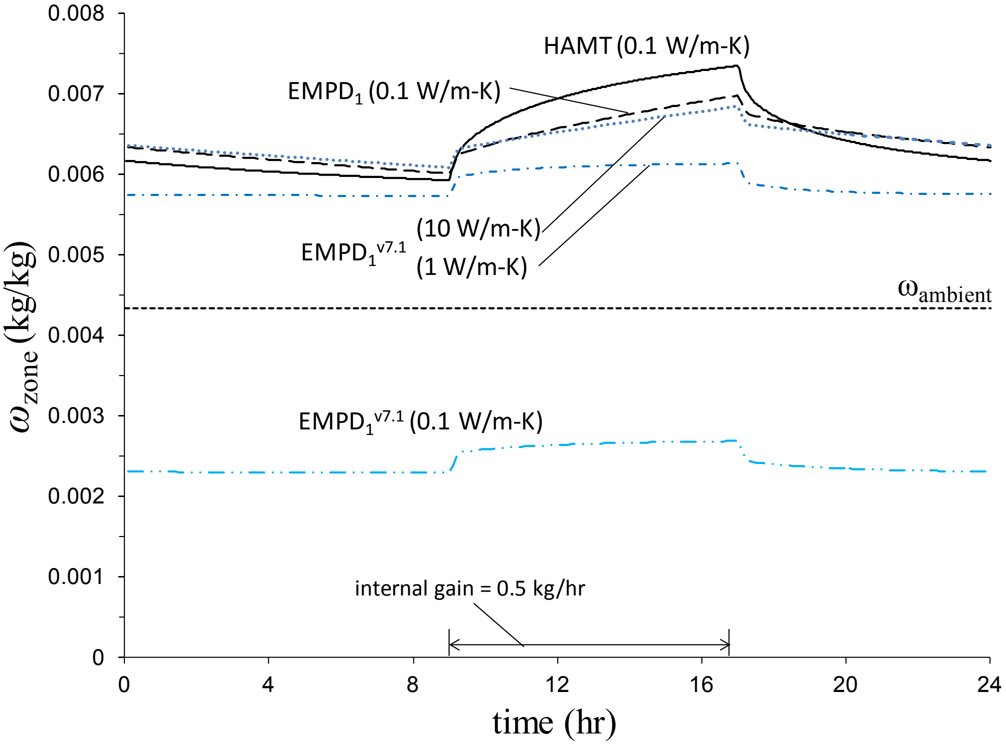

Figure 5. Predicted zone humidity for non-isothermal HAMT and EMPD_1 models. EMPD_1 = model in EnergyPlus v7.2, $\text{EMPD}_1^{v7.1}$ = model in EnergyPlus v7.1 and earlier. Note that the y-axis was expanded relative to previous figures.

3.3 Case 2: Cyclical Ambient Humidity

Case 1 was used to illustrate differences between the moisture models' responses to a simple forcing function, compare this response to an analytical solution, and uncover problems with the $\mathrm{EMPD}_1^{v7.1}$ model in EnergyPlus. Case 1, though, is far from a realistic building and realistic loads. Case 2 moves incrementally toward reality by considering sinusoidal-varying ambient humidity. The frequency of this sine wave was selected to not coincide with a multiple of the daily fluctuations. This gives more diverse latent loads by combining the ventilation and internal gain in different ways throughout the two-month simulation period.

Moving from a constant ventilation load to a sinusoidal-varying one is important for two reasons: (1) the added complexity can amplify the small differences between the models seen in Figure 3; and (2) the EMPD model relies on a cyclical humidity load to estimate the penetration depth. The EMPD_2 model uses two values: one for a short-term buffer, and one for a deep buffer. Thus, with this case, which has two well-defined cycle periods, both values (d_{EMPD} and $d_{EMPD\text{-}deep}$) can be calculated. The EMPD_1 model uses only one penetration depth, and cannot account for both frequencies at the same time.

Figure 6 shows the zone humidity predicted by the four models over a 7-day period of the simulation. If, as expected, the HAMT model is assumed to be the "correct" response, the EMPD_2 model appears to be the most accurate. We quantify this accuracy by calculating, at each time step, the percent difference between the zone humidity predicted by the HAMT model and that predicted by the other models. We plot these differences, or *errors*, in a histogram (Figure 7), where the bins are centered at the label on the x-axis (e.g., –5% bin is –2.5% to –7.5%).

Figure 7 shows that the EMPD_2 model matches the HAMT model within ±10% at all time steps, and is within ±2.5% for 40% of the simulation. The EC model does not match the HAMT model, with errors up to 25%. The EMPD_1 model is not much better than the EC model. Two questions arise: (1) What accounts for the large difference between the EMPD_1 and EMPD_2 model formulations? and, (2) with the similar results between the EC and EMPD_1 models, are there any advantages to the EMPD_1 model over the EC model?

For the first question, there are a few possibilities, but we found that the primary cause was that the EMPD_2 model includes a deep buffer to account for longer term fluctuations. We verified that this accounted for most of the difference by simulating the EMPD_2 model *without* a deep layer. The results from this simulation (not shown in figure for clarity) have the same day-to-day shape as the EMPD_2 response in Figure 6, but are stretched to line up with the EMPD_1 response. This indicates that a deep layer is necessary to account for long-term cycles in humidity loads in addition to the typical daily humidity cycles. Two other reasons for the differences are that the equations are solved differently, as discussed in Section 2.3, and that the EMPD_2 model is isothermal and EMPD_1 is non-isothermal. These two reasons account for some of the difference, but they affect the day-to-day shape of the building humidity and do not account for the differences in the long-term fluctuations. These day-to-day effects can be seen in Figure 3 and Figure 4.

To answer the second question, note that the close overlap of the EC and EMPD_1 model for this case is coincidental. The EC of 15 is based on empirical data for real buildings, including furnishings; this is not the building simulated here. However, it indicates that the responses can be similar, depending on the parameters used. The EC model requires only an effective capacitance multiplier; the $EMPD_1$ model requires d_{EMPD}, $du/d\phi$, and the surface area of the walls and furnishings. The EC multiplier is simple, but has a weak link to reality; it is hard to estimate without experimental data. The three parameters for the $EMPD_1$ model can still be difficult to estimate, but they do have a better link with reality. Adjusting the $EMPD_1$ model is relatively straightforward if, for example, the wall area doubles or if a material in the zone is replaced with a higher permeability material.

The loads used in this case (internal gain and ventilation) were cyclical. In other words, d_{EMPD} for both the surface and deep layers can be calculated for the $EMPD_2$ model. This is not the case in reality. Loads, even in a simulation, are highly variable, which is certainly the case for the weather. This is explored in Section 3.4.

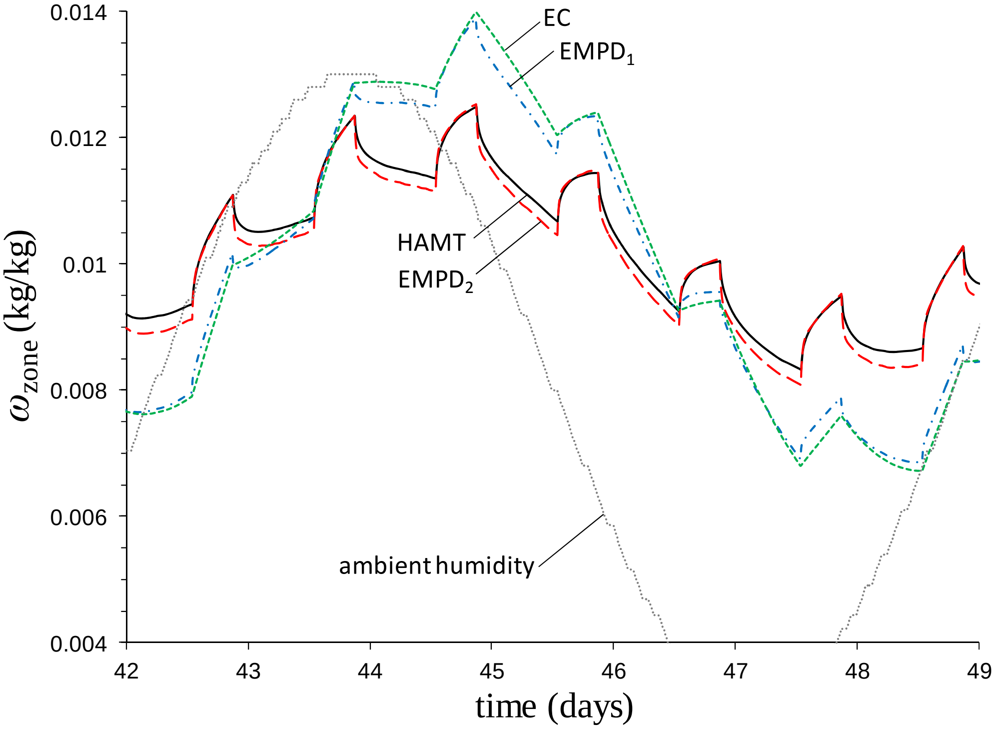

Figure 6. Predicted zone humidity over a one-week period during simulations with cyclical ambient humidity

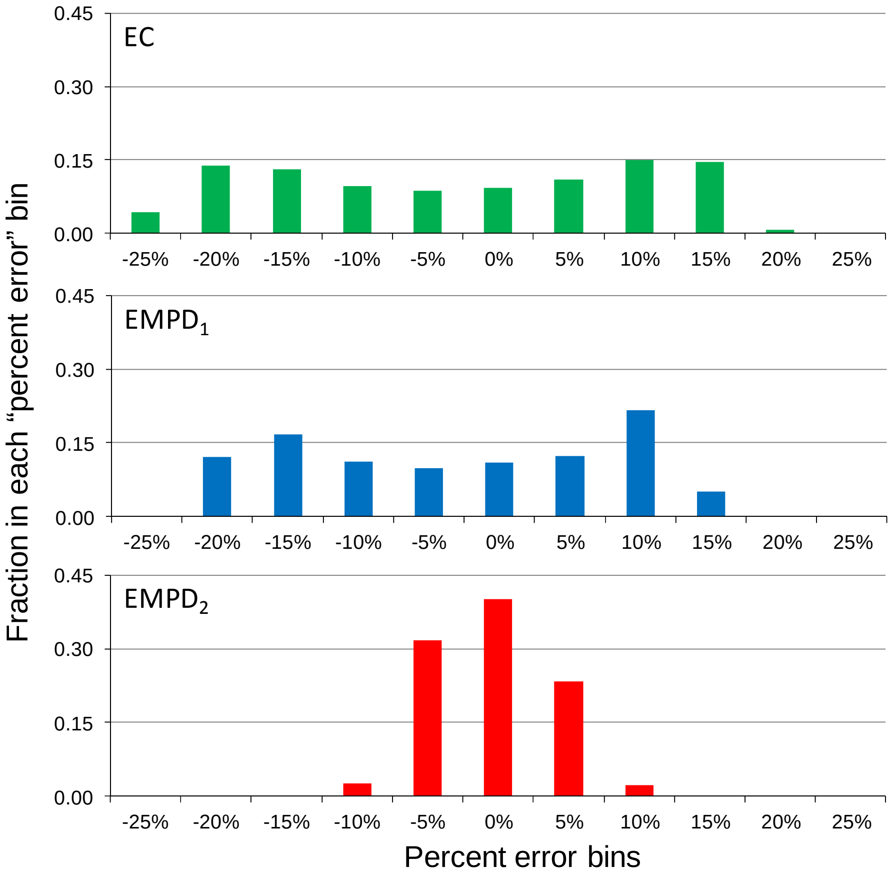

Figure 7. Histogram of errors for EC, EMPD$_1$, and EMPD$_2$ model during simulations with cyclical ambient humidity. Error is calculated as deviation from HAMT model.

3.4 Case 3: Ambient Humidity From Weather Data

We move still further toward reality with case 3, which uses ambient humidity weather data. Note that the ambient temperature is still fixed at 28°C; we are imposing a latent ventilation load on the building, but not a sensible load. As in Section 3.3, a sample period from these simulations is shown in Figure 8 (two weeks in this case), and a histogram for each model showing their deviations from the HAMT model are shown in Figure 9.

The results for the EMPD$_2$ model indicate that the deep layer thickness of 21 mm seems appropriate, as its deviations from the HAMT model are similar to those for the sinusoidal humidity case. The results are relatively insensitive to the deep layer thickness, with changes of the deep-layer thickness by ±25% changing the zone humidity by 0.1% on average, and by a maximum of 3%. The EMPD$_1$ model again shows similar results to the EC model.

Similar to the last case, the large deviations of the EMPD$_1$ model from the HAMT model result from the lack of a deep buffer layer. Thus, for the case considered here, including a deep buffer layer is critical. But are there instances where a deep layer is not needed? Figure 3 shows that it loses its importance for the case where the humidity load is a single, repeated cycle, as opposed to a short-term and a long-term cycle. The properties of the buffering materials also affect the importance of the deep layer. For example, if the concrete used in this example were only 10 mm thick, a deep layer thickness of 21 mm would overestimate the buffering. Generally, this deep layer should always be thinner than the total material. If we calculate a surface layer thickness (τ_p = 1 day) and deep layer thickness (τ_p = 7 days) for a few common materials, we get on the order of 10 mm and 25 mm for drywall, 15 mm and 30 mm for soft fabric-like materials, and 1 mm and 5 mm for wood. These calculations indicate that wood, like concrete, will generally need a deep layer thickness. Drywall will also, but it will usually be thinner than the calculated 25 mm because drywall is typically 12-15 mm thick. Some fabric-like materials may require a deep layer (e.g., carpet with pad); others may not (e.g., window curtains).

These more nuanced calculations emphasize the difficulty of predicting the moisture properties to predict humidity in buildings. Future work is planned to understand the sensitivity of the EMPD model results to both the material properties and to the surface and deep layer thicknesses.

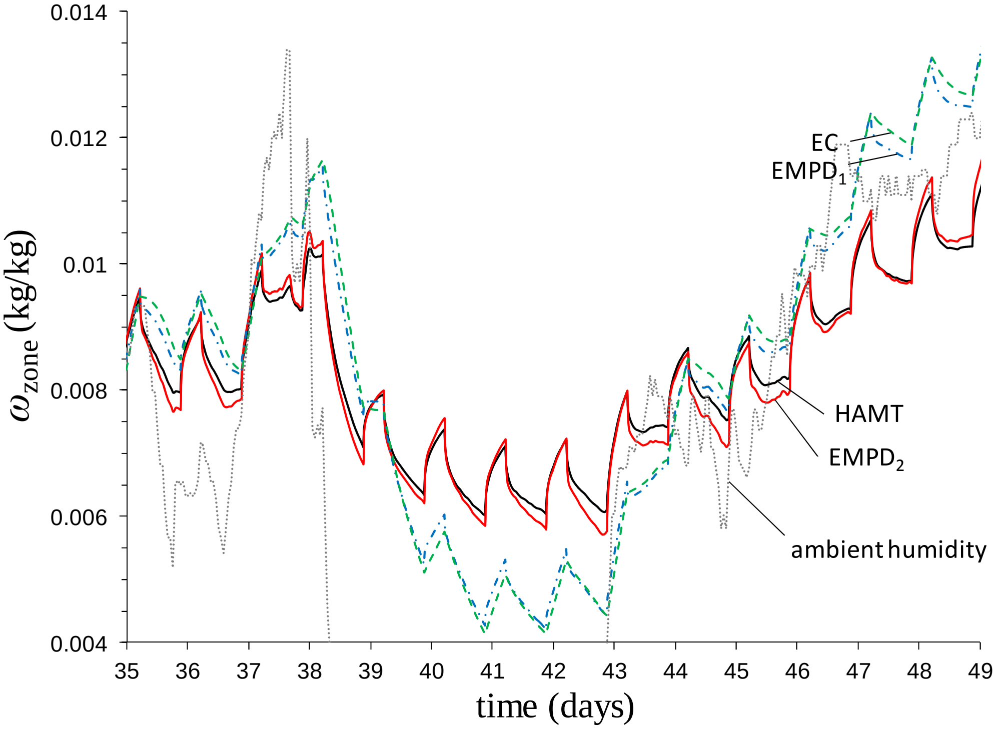

Figure 8. Predicted zone humidity over a two-week period during simulations with ambient humidity from weather data

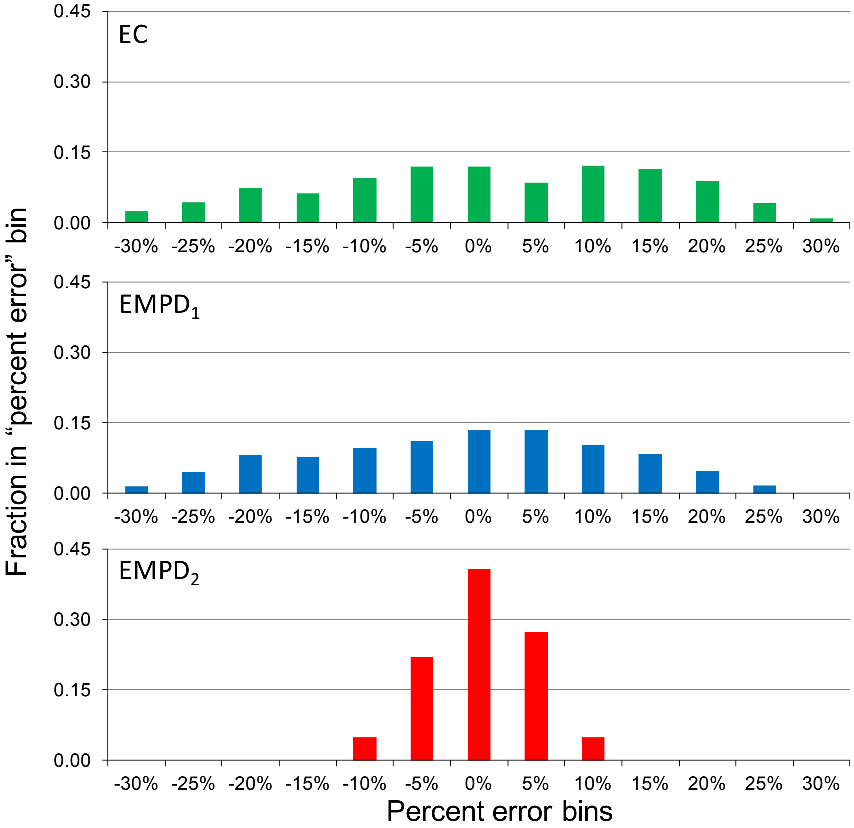

Figure 9. Histogram of errors for EC, EMPD$_1$, and EMPD$_2$ model during simulations with ambient humidity from weather data. Error is calculated as deviation from HAMT model.

4 Conclusions

The goals of this research are to look at the dynamics of moisture models and discuss their differences. Our intent is not to endorse, or condemn, a particular model. Moisture transfer through a building envelope is complex and not well enough understood to conclude that one model is more accurate than another without data from real buildings. That being said, the following conclusions were drawn from this research:

- The HAMT and EMPD$_2$ models are close to the isothermal analytical solution. Assuming the HAMT model is "correct," the EMPD$_2$ model is still reasonably accurate for more complex cases (a varying latent ventilation load) and has the advantage of a much lower simulation run time. The inclusion of the deep buffer layer in the EMPD$_2$ model was critical in achieving this accuracy for the case considered here. Some user insight is required in calculating this $d_{EMPD\text{-}deep}$ value. In general, the inclusion of a deep buffer layer is more important for thick materials with a steep slope in the moisture capacitance curve and a low moisture diffusivity.
- The advantage of the EC model is its simple implementation. Its response seems less realistic than the others based on these simple cases, but in more complicated cases other factors could drown out these inaccuracies, particularly for cases where a deep buffering layer is unimportant.
- The EMPD$_1$ model in EnergyPlus versions earlier than 7.2 leads to significant errors, and should not be used. Previous results from this model should be used with caution, particularly for simulations with a high Ψ-parameter (see the Appendix). The issue has been fixed in EnergyPlus version 7.2.
- The EMPD$_1$ model available in EnergyPlus version 7.2 is an improvement over the EC model, with more realistic responses to humidity loads (Figure 3). It does not appear to be much improved over the EC model for more complex loads, but the parameters can be derived from physical entities (surface area, moisture sorption curve, and permeability), unlike the EC value, which is empirical (or a guess).

These conclusions lead to the following next steps:

- There is a need to better understand the sensitivities of the EMPD model to its input parameters, particularly the penetration depth. This would indicate how carefully this penetration depth needs to be calculated or selected. Next steps in this research are to develop a systematic, reliable method for determining this penetration depth for different buildings and humidity loads.
- A more in-depth study is needed on the impacts of using an isothermal assumption (i.e., is an isothermal model adequate?). This will be more important for some cases than others. For example, a simulation that controls zone temperature to a single value will likely be less affected than a zone with a varying temperature, such as during the swing seasons or from a thermostat setback. In addition to this zone-temperature effect, the material properties are also important. All else being equal, low-conductivity materials will have a higher surface temperature during moisture sorption than high-conductivity

materials. The ratio of the material's moisture effusivity to its thermal effusivity, similar to the ψ-parameter in the Appendix, could likely be used to gauge the importance of the isothermal assumption for a given building load.

- For the cases considered, the $EMPD_2$ model performed better than the $EMPD_1$ model, and may be preferred for a model in EnergyPlus. However, the $EMPD_2$ model, as it is currently formulated, uses an isothermal assumption. If an isothermal assumption is inappropriate, developing a non-isothermal $EMPD_2$ model will be valuable.

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Appendix

To look more in depth at the problems with the $\mathrm{EMPD}_1^{v7.1}$ implementation, we simulated 40 cases with different material properties. This is not an exhaustive analysis of this model, nor is it meant to be an evaluation of its accuracy. Rather, it is a means to illustrate the problems with the model and to identify simulation conditions that amplify or lessen these problems.

The material properties were selected randomly from a uniform distribution between roughly 40% and 250% of the nominal values in Table 2. The $\mathrm{EMPD}_1^{v7.1}$ and EMPD_1 models were evaluated by looking at the ratio of their peak humidity prediction ($\omega_{\mathrm{zone,max}}$) with the peak humidity prediction of the HAMT model. This differs from the comparisons based on the humidity rise used in previous sections.

These ratios for the 40 simulations (Figure A.1) show that the $\mathrm{EMPD}_1^{v7.1}$ model predictions are worse (i.e., move closer to the lowest $\mathrm{EMPD}_1^{v7.1}$ line in Figure 5) as the thermal effusivity, e_{th}, decreases and the moisture effusivity, e_m, increases. These are defined as:

$$e_{th} = \sqrt{k\rho_{dry}c_p} \tag{A.1}$$

$$e_m = \sqrt{\frac{\delta_{perm}\rho_{dry}\left(\partial \mathrm{u}/\partial\phi\right)}{p_{sat}}} \tag{A.2}$$

where k is the material thermal conductivity, and c_p the specific heat capacity.

In addition to the effusivities, the wall thickness, L, and simulation time step, Δt, also have an effect. The data correlates reasonably well with the following parameter, which is used on the x-axis in Figure A.1:

$$\Psi = \frac{e_m}{e_{th}}\frac{1}{\sqrt{L\Delta t}} \tag{A.3}$$

Figure A.1 shows that the fixed EMPD_1 model is close to the HAMT model.

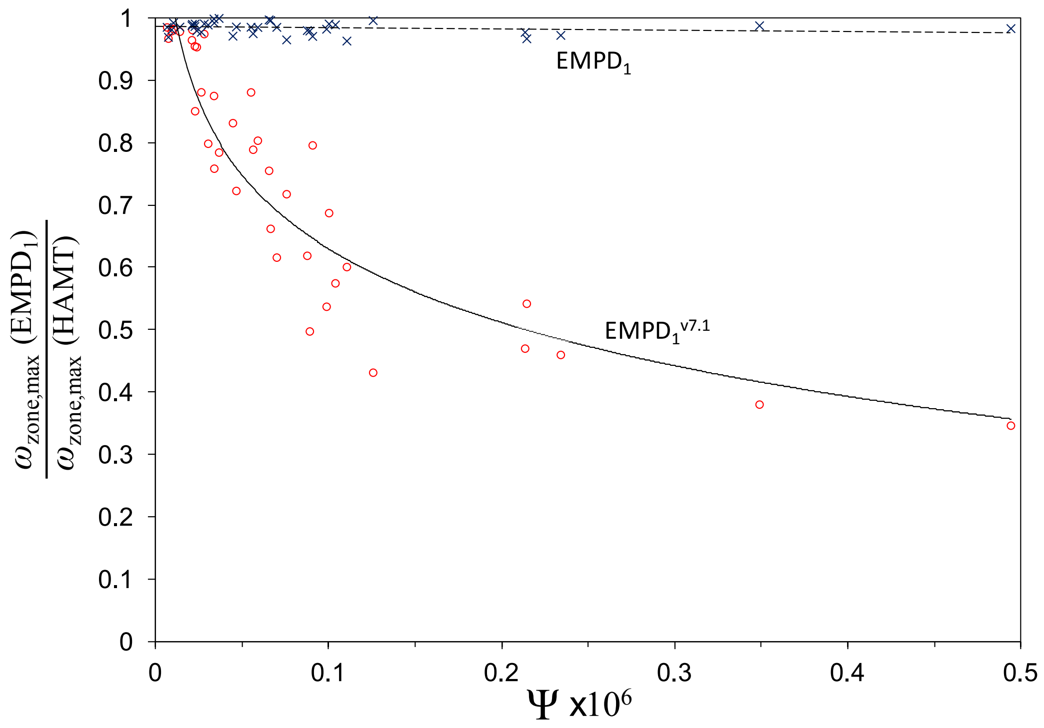
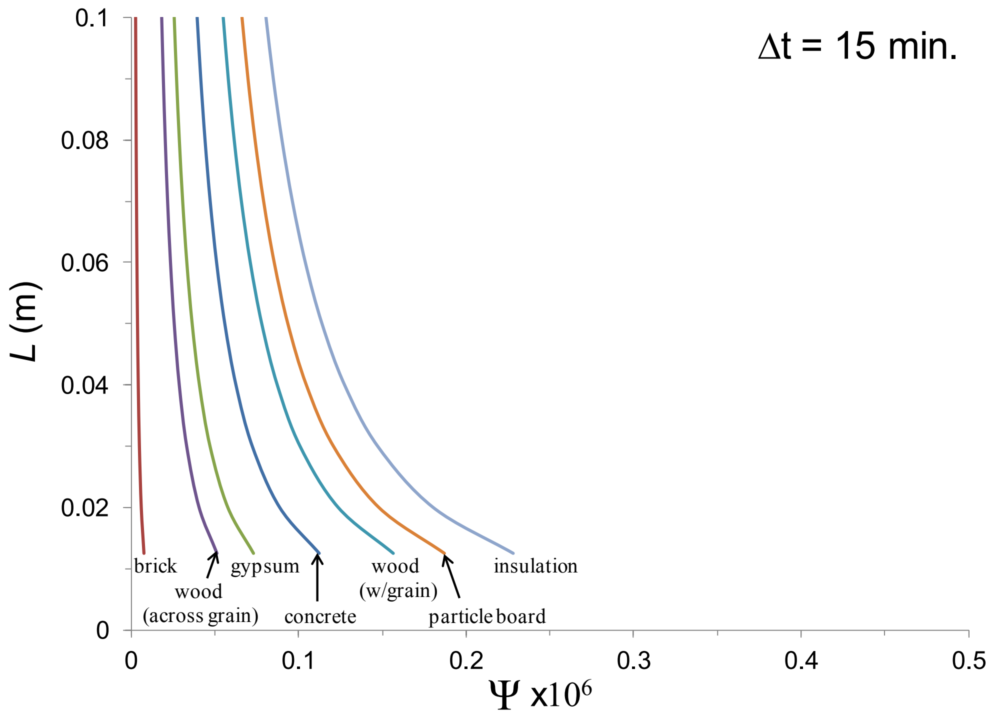
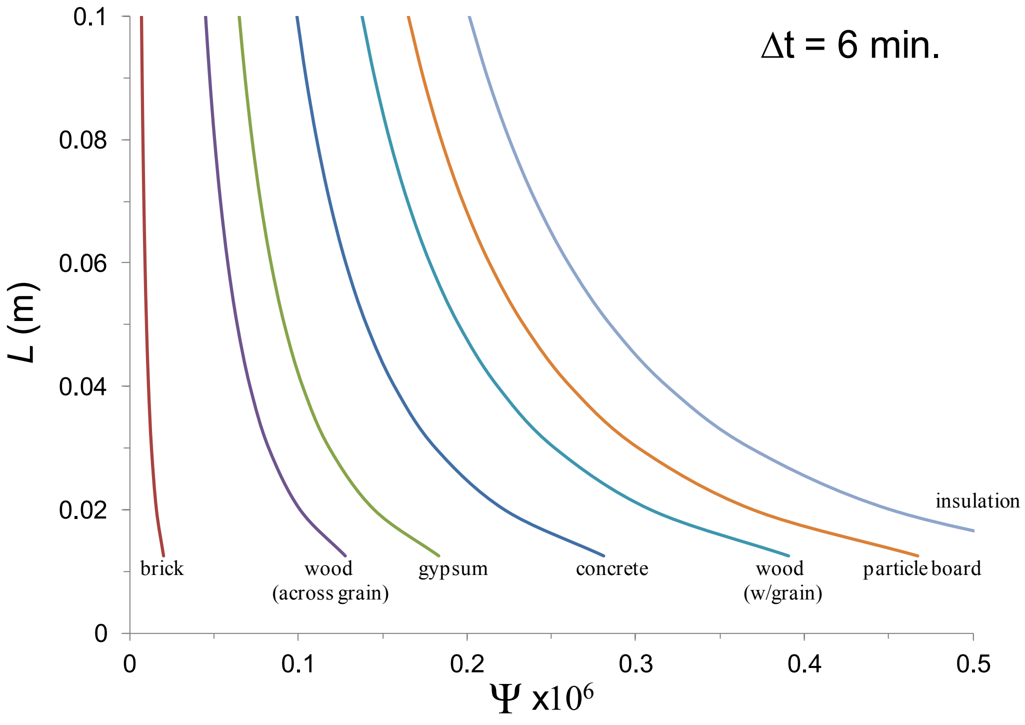


Figure A.1. Peak humidity ratio of EMPD$_1$ (×) and EMPD$_1^{v7.1}$ (○) simulations relative to HAMT simulations versus ψ-parameter (defined in Eq. (A.3))

Does the low humidity predicted by the EMPD$_1^{v7.1}$ model, as shown in Figure A.1, mean that any results from the EMPD model in EnergyPlus versions earlier than 7.2 are incorrect? Not necessarily; it depends on the Ψ-parameter for that simulation. Low values are likely to be more accurate. This Ψ-parameter is linked to actual material properties in Figure A.2, which shows the Ψ-parameter for different materials for a range of thicknesses and two different time steps. For easier comparison with Figure A.1, the dependent variable (Ψ) is on the horizontal axis. Figure A.2 shows that the EMPD$_1^{v7.1}$ implementation is inappropriate for many combinations of materials, especially when those materials are thin and when the simulation is solved with a small time step.



(a)



(b)

Figure A.2. Ψ-parameter for different materials of different thickness: (a) 15-minute time step, (b) 6-minute time step