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Effective moisture penetration depth model for residential buildings: Sensitivity analysis and guidance on model inputs

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ABSTRACT

Moisture buffering of building materials has a significant impact on the building's indoor humidity, and building energy simulations need to model this buffering to accurately predict the humidity. Researchers requiring a simple moisture-buffering approach typically rely on the effective-capacitance model, which has been shown to be a poor predictor of actual indoor humidity. This paper describes an alternative two-layer effective moisture penetration depth (EMPD) model and its inputs. While this model has been used previously, there is a need to understand the sensitivity of this model to uncertain inputs. In this paper, we use the moisture-adsorbent materials exposed to the interior air: drywall, wood, and carpet. We use a global sensitivity analysis to determine which inputs are most influential and how the model's prediction capability degrades due to uncertainty in these inputs. We then compare the model's humidity prediction with measured data from five houses, which shows that this model, and a set of simple inputs, can give reasonable prediction of the indoor humidity.

1. Introduction

Building energy simulations are used to predict a building's indoor conditions and to determine the energy needed to keep these conditions comfortable. The indoor humidity has a significant effect on comfort and indoor air quality, and needs to be calculated to get a full picture of the building conditions and the performance of its heating, ventilating, and air-conditioning (HVAC) equipment. Indoor moisture is of particular concern in efficient, low-load houses [1]. The adsorption of moisture into (and desorption out of) building materials impacts indoor humidity and needs to be included in building energy simulations.

There are several methods used in building energy simulations to account for the moisture buffering of materials [2,3]. They range from a multiplier on the moisture capacitance of the air (effective capacitance) to a detailed finite-difference approach, where moisture diffusion is calculated within each of the materials in the building [4]. This paper focuses on a two-layer effective moisture penetration depth (EMPD) approach, which has been shown to be accurate when given appropriate inputs [5–10], including when the material property inputs were derived empirically [11–13]. This EMPD model was recently added to the building energy simulation program EnergyPlus [14].

The simpler effective capacitance model is often used in building simulation tools to predict indoor humidity for different buildings and climates, or to evaluate humidity control options for buildings (e.g., [15,16]). This simpler model is often used because of its single parameter input, and due to a lack of standard inputs for the general modeling community to use for more complex models. The EMPD model has been shown to be significantly more accurate than the effective capacitance model at predicting indoor humidity, and the effective capacitance model is incapable of buffering loads of different frequencies due to its single input [8,9]. This means that the effective capacitance model cannot be calibrated to match the actual indoor humidity except for extremely simple cases. Although the EMPD model has been used previously by several researchers [6–8,10,17–20], there is a need for a better understanding of how this model handles uncertainty in its inputs.

The purpose of this paper is to describe the inputs for the two-layer EMPD model, specifically for residential buildings, to determine which inputs are most influential, and to quantify the model's prediction capability due to a range of uncertainties in these inputs. The results of this sensitivity analysis will provide guidance to researchers who want to use a more realistic moisture buffering model in their building energy simulations, without requiring a detailed finite-difference approach. The paper concludes by comparing the prediction of this model using a simple set of inputs to field data from several houses.

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List of symbols

a, b, c, d	dimensionless coefficients in moisture sorption curve, Eq. (1)
A_{surf}	surface area of moisture-sorbent material (m^2)
a_T	temperature coefficient for the natural infiltration correlation
a_W	wind coefficient for the natural infiltration correlation
CV(RMSE)	coefficient of variation of the root-mean-square error
d_{EMPD}	effective moisture penetration depth (m)
$\dot{m}_{inf}$	infiltration/ventilation air flow rate ($kg\,s^{-1}$)
$\dot{m}_{NatInf}$	natural infiltration air flow rate ($kg\,s^{-1}$)
$\dot{m}_v$	moisture transfer rate ($kg\,s^{-1}$)
N	number of humidity measurements for CV(RMSE) calculation
n_T	temperature exponent in natural infiltration correlation
n_W	wind exponent in natural infiltration correlation
P	pressure (Pa)
$PermConv_{IP\text{-}SI}$	conversion from perm rating to SI units ($kg\,m^{-2}\,s^{-1}\,Pa^{-1}$)
PermRating	permeance of material coating in perms
p_{sat}	saturated vapor pressure (Pa)
R	mass transfer resistance ($s\,Pa\,m^2\,kg^{-1}$)
$\mathcal{R}$	universal gas constant ($461.52\,J\,kg^{-1}\,K^{-1}$ for water)
S_i	sensitivity index for input variable x_i
T	temperature (°C)
t	time (s)
u	moisture content of the material $kg \cdot kg^{-1}$)
V_{zone}	volume of the zone air (m^3)
V_{wind}	wind speed (m/s)

Greek symbols

δ_p	permeability ($kg\,m^{-1}\,s^{-1}\,Pa^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	standard deviation
ϕ	relative humidity
ω	humidity ratio (kg_{vapor}/kg_{air})

Subscripts

1	surface layer
2	deep layer
air	property of air; building zone air
amb	ambient air
baseline	baseline input values from Tables 2 and 3
BL	boundary layer
coating	material coating, such as paint
crawlspace	property of air in the crawlspace in the Mayfair house
equip	HVAC equipment
gain	moisture from internal latent gains
matl	property of material
measured	value from field measurements
model	value based on numerical model
t – 1	previous timestep
zone	building zone air

2. Methods

This section is split into four parts: (1) a description of the equations and assumptions used in the EMPD model, (2) the experimental data from five houses to compare to the model, (3) the methods for estimating the EMPD inputs for these five houses, and (4) the sensitivity analysis methods.

2.1. EMPD model

The EMPD concept is based on the assumption of cyclic variations in humidity, and therefore the mass-based moisture content, *u*, of the material. This is generally a reasonable assumption for buildings, with cyclic daily internal latent gains and air conditioner use. The EMPD model uses a thin material layer of constant thickness at each material surface. The moisture content is assumed constant across this thickness, termed the surface penetration depth.

The EMPD model was developed several decades ago [17,21,22], and thus we do not focus on the derivation of the model. Instead, this section focuses on a particular implementation, with two fictitious layers of material with uniform moisture content: a surface layer, which accounts for short-term moisture buffering, and a deep layer, which accounts for longer-term moisture buffering. The model calculates the moisture transfer between the air and the surface layer and between the surface layer and the deep layer. Our previous research [8,12] has shown that this deep layer is important, and neglecting it will lead to a significantly worse prediction of the zone humidity.

Fig. 1 shows how these layers are connected to each other and to the zone air. Each node is characterized by its humidity ratio, ω, which for the surface (ω_1) and deep (ω_2) layer nodes is an equivalent humidity ratio based on the material moisture content. The moisture content and humidity are connected through the sorption curve, which is a function of the relative humidity (ϕ). The following relation is used here [21]:

$$u = a\phi^b + c\phi^d \tag{1}$$

where *a* through *d* are empirical coefficients. The humidity ratio and relative humidity are related through:

$$\omega = \frac{0.622\,p_{sat}\phi}{P_{amb} - p_{sat}\phi} \tag{2}$$

where P_{amb} is the ambient pressure, and p_{sat} is the saturated vapor pressure at the temperature of the material. This equation is used for both the surface and deep layers.

Water vapor transfer ($\dot{m}_v$) between the nodes in Fig. 1 is calculated as the difference in humidity ratios divided by the mass-transfer resistance. Moisture transfer into the surface layer node (1) is:

$$\dot{m}_{v,1} = \frac{(\boldsymbol{\omega_{zone}} - \boldsymbol{\omega}_1)}{\boldsymbol{R}_1} + \frac{(\boldsymbol{\omega}_2 - \boldsymbol{\omega}_1)}{\boldsymbol{R}_2} \tag{3}$$

and into the deep layer node (2) is:

$$\dot{m}_{v,2} = \frac{(\omega_1 - \omega_2)}{R_2} \tag{4}$$

The mass transfer resistance between the surface layer and the zone (R_1) includes three resistances in series: a boundary-layer resistance (R_{BL}), a coating resistance ($R_{coating}$) (e.g., paint), and the diffusive resistance into the material ($R_{diff,SL}$).

$$R_1 = R_{BL} + R_{coating} + R_{diff,SL} \tag{5}$$

where

$$R_{diff,SL} = \frac{d_{EMPD,1}}{2\rho_{air}\mathcal{R}T\delta_{perm}} \tag{6}$$

The parameters in the diffusive resistance include the surface-layer penetration depth ($d_{EMPD,1}$), air density (ρ_{air}), the universal gas constant ($\mathcal{R} = 461.52$ J/kg K for water), temperature (*T*), and