Energy and Buildings 117 (2016) 91–98

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Field measurement of moisture-buffering model inputs for residential buildings

Jason Woods*, Jon Winkler

National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA

ARTICLE INFO

Article history:
Received 19 October 2015
Received in revised form 3 February 2016
Accepted 4 February 2016
Available online 5 February 2016

Keywords:
Moisture capacitance
Buildings
Modeling
Moisture buffering
Effective penetration depth

ABSTRACT

Moisture adsorption and desorption in building materials impact indoor humidity. This effect should be included in building-energy simulations, particularly when humidity is being investigated or controlled. Several models can calculate this moisture-buffering effect, but accurate ones require model inputs that are not always known to the user of the building-energy simulation. This research developed an empirical method to extract whole-house model inputs for the effective moisture penetration depth (EMPD) model. The experimental approach was to subject the materials in the house to a square-wave relative-humidity profile, measure all of the moisture-transfer terms (e.g., infiltration, air-conditioner condensate), and calculate the only unmeasured term—the moisture sorption into the materials. We validated this method with laboratory measurements, which we used to measure the EMPD model inputs of two houses. After deriving these inputs, we measured the humidity of the same houses during tests with realistic latent and sensible loads and demonstrated the accuracy of this approach. These results show that the EMPD model, when given reasonable inputs, is an accurate moisture-buffering model.

1. Introduction

Building-energy simulations can be used to predict a building's indoor conditions and determine the energy needed to keep these conditions comfortable. These models simulate the loads on the building (e.g., internal gains and envelope heat transfer), determine the operation of the space-conditioning equipment, and then calculate the building's temperature and humidity throughout the year. The indoor temperature and humidity are affected not only by the latent and sensible loads and the space-conditioning equipment, but also, by the capacitance of the building materials that buffer changes in temperature and humidity.

For example, a sensible load changes the air temperature in an empty house with lightweight walls more quickly than in a furnished house with heavy walls, because much of the thermal energy is stored in the furnishings and the heavy walls rather than in the air. This can have a considerable effect on energy use, because the diurnal temperature variation can be buffered by this thermal capacitance. This capacitance is included in most building-energy models.

Similar to the thermal capacitance's effect on temperature, the moisture capacitance of a building's materials is important for predicting the indoor humidity. The materials adsorb[1] or desorb moisture depending on changes in relative humidity (RH) of the surrounding air. This moisture transfer buffers changes in humidity. Calculations of moisture storage and transport are often simplified or ignored in building-energy models. Even though the simplified models often adequately predict energy use, they do not adequately predict the indoor RH, nor do they predict the correct energy use when humidity is controlled [1]. Predicting RH in homes has become important as envelope and lighting improvements have reduced the sensible load, while the latent load from internal gains and required ventilation has remained relatively constant [2,3]. This can result in increased humidity and may require dehumidification equipment to maintain comfort and prevent moisture-related problems such as mold growth. Accurately predicting the indoor RH is essential to understanding these potential problems and to properly evaluating and selecting potential solutions.

[1] Moisture *ad*sorption onto a material's surface (including its internal pore structure) and *ab*sorption into the bulk material are collectively known as *sorption*. Both adsorption and absorption occur in building materials (adsorption at lower humidity, absorption at higher humidity). Adsorption is used in this paper to mean either type of sorption.

* Corresponding author. Tel.: +1 303 384 6189.
E-mail address: jason.woods@nrel.gov (J. Woods).

http://dx.doi.org/10.1016/j.enbuild.2016.02.008
0378-7788/

Nomenclature

List of symbols

A	surface area of moisture-sorbent material (m^2)
CV(RSME)	coefficient of variation of the root-mean-square error
d_{EMPD}	effective moisture penetration depth (m)
k	mass transfer coefficient ($m\,s^{-1}$)
M_{scale}	scale reading (kg)
M_v	cumulative moisture transfer (kg)
$\dot{m}_v$	moisture transfer rate ($kg\,s^{-1}$)
m_r	slope of initial ramp in RH during step-change tests ($RH\,s^{-1}$)
N	number of measurements for CV(RSME) calculation
P	pressure (Pa)
p_{sat}	saturated vapor pressure (Pa)
RH	relative humidity
T	temperature (°C)
t	time (s)
V_{zone}	volume of zone air (m^3)
V_{wind}	wind speed ($m\,s^{-1}$)
w	moisture content ($kg\,m^{-3}$)

Greek symbols

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

subscripts

air	property of air; building zone air
avg	average
deep	property/quantity for the deep layer
f	final
gain	moisture with internal gain
HVAC	moisture removed with heating or air conditioning equipment
inf	infiltration
matl	moisture associated with moisture-sorbent material
meas	measured value
model	modeled value
surf	property/quantity for the surface layer
zone	building zone air

The simplest method for including moisture capacitance in modeling is to increase the capacitance of the air in the building to account for the added capacitance of the materials. This effective capacitance (EC) model assumes that the volume of the air in the building is 10–15 times larger than the actual volume [4–6]. This model is not only unrealistic, but it also cannot be calibrated to give an accurate humidity response [1].

A complex method for studying moisture capacitance and moisture flows in building modeling is the finite-difference method, which spatially discretizes the differential equations within the material [7,8]. This approach is accurate but requires long simulation times and several model inputs that are often unknown.

Another approach is the effective moisture penetration depth (EMPD) model [9–11]. This model assumes that the moisture is transferred between the zone air and a thin fictitious layer of material of uniform moisture content. The basis for this model is that the zone humidity is cyclical. If it is perfectly cyclical (e.g., a sine wave), then the model gives nearly the exact solution. If it is not perfectly cyclical, then it can still be a good approximation [12]. The EMPD model offers a more realistic approach than the EC model and a simpler approach than the finite-difference method.

The EMPD model requires inputs for the moisture properties (e.g., permeability, moisture sorption curve) and the surface areas for each material in the house. However, a single test can be used to measure these properties in aggregate, as several researchers have demonstrated [13–18]. Vereecken et al. [19] demonstrated an experimental method for simultaneously measuring a single set of EMPD model inputs for multiple materials. In this research, we extended that method to measure the moisture-buffering model inputs for a whole house in the field.

The goal of this research was to measure and validate aggregate EMPD model inputs for use in a building-energy simulation. Three key elements were needed to achieve this goal:

(1) The ability to measure moisture transfer into and out of materials in a house in the field. Established methods for doing this, typically used in a laboratory, directly weigh the material as it adsorbs moisture; this is not feasible for a whole house.
(2) A humidity profile that enables a fast, accurate, and reliable method for extracting the model inputs from measured moisture adsorption/desorption data.
(3) Data that can validate the model and these extracted model inputs.

The research described in this paper addresses these three needs.

2. Test houses

Two unoccupied test houses were used in this research: a laboratory house at the Florida Solar Energy Center in Cocoa, Florida, and a production house in a neighborhood in Stockton, California.

House A: The first test house is one of two that comprise the Flexible Residential Test Facility [20], which was built in 2010. These houses are single-story, slab-on-grade construction with painted, uninsulated concrete block walls and R-19 attic insulation. The inside of the exterior walls has furring strips and painted drywall. The 143 m^2 floor area is one large empty room. Furniture, carpet, and interior walls were added to the space. The interior walls consist of 16″ (40.6-cm) on-center 2 × 4 studs and two sheets of 12.5-mm drywall. They were not installed per a floor plan; rather, they were built in 2.4 m × 1.2 m sections and dispersed throughout the space to ensure a single zone with uniform conditions. Added furniture included three bedroom sets (with linens), kitchen table and chairs, and living room furniture. We covered all windows with 25 mm polyisocyanurate foam to eliminate the effects of solar gains and to ensure that no condensation formed on the single-pane windows. Exterior and interior photos of House A, including the moisture measurement equipment, are shown in Figs. 1 and 2. For more information and additional photographs of House A, see [20,21].

House B: The second house, in Stockton, California, was built in 2005 and is two stories. The exterior walls consist of 16″ (40.6-cm) on-center, 2 × 4 studs with blown-in fiberglass insulation and 25 mm of exterior rigid expanded polystyrene insulation. The attic has R-30 of blown-in fiberglass. Furnishings for House B included the same as House A, plus office furniture, 19 kg of clothing and linens, and 30 kg of paper and cardboard. Exterior and interior photos of House B are shown in Figs. 3 and 4, including both (a) upstairs (where the moisture measurement equipment was installed), and (b) downstairs. For more information and additional photographs of House B, see “Caleb” house in [22].