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Effect of occupant behavior and air-conditioner controls on humidity in typical and high-efficiency homes

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ABSTRACT

Increasing insulation levels and improved windows are reducing sensible cooling loads in high-efficiency homes. This trend raises concerns that the resulting shift in the balance of sensible and latent cooling loads may result in higher indoor humidity, occupant discomfort, and stunted adoption of high-efficiency homes. This study utilizes established moisture-buffering and air-conditioner latent degradation models in conjunction with an approach to stochastically model internal gains. Building loads and indoor humidity levels are compared for simulations of typical new construction homes and high-efficiency homes in 10 US cities. The sensitivity of indoor humidity to changes in cooling set point, air-conditioner capacity, and blower control parameters are evaluated. The results show that high-efficiency homes in humid climates have cooling loads with a higher fraction of latent loads than the typical new construction home, resulting in higher indoor humidity. Reducing the cooling set point is the easiest method to reduce indoor humidity, but it is not energy efficient, and overcooling may lead to occupant discomfort. Eliminating the blower operation at the end of cooling cycles and reducing the cooling airflow rate also reduce indoor humidity and with a smaller impact on energy use and comfort.

1. Introduction

Homes in the United States are becoming more efficient each year. The average energy consumption per housing unit has steadily decreased since 1980 [1]. This is partially attributable to increasing insulation levels and the use of more efficient windows that are reducing the sensible heat transfer through the building envelope. More-efficient lighting and appliances further reduce building sensible cooling loads. However, moisture generated inside a home by occupants and their activities is unchanged. Typical air-conditioning systems operate using a thermostat that only controls temperature and therefore only responds to sensible loads. This has led to concerns that homes with low sensible loads (low-load homes) will experience indoor humidity levels that are higher than those of typical homes, potentially causing occupant discomfort [2]. To ensure that low-load homes are accepted by homeowners, the homes must provide comfort, including indoor humidity control, that is equivalent to or better than that of conventional homes.[1]

Several studies have evaluated different aspects of indoor humidity and dehumidification in residential homes. Rudd and Henderson [3] presented field data from 43 homes in various climate regions throughout the country, including six hot-humid cities. The study concluded that low sensible heat gain coupled with continuous mechanical ventilation in high-performance homes significantly increased the number of hours requiring supplemental dehumidification.

Henderson et al. [4] conducted a study using TRNSYS simulation software to analyze space-conditioning equipment with and without humidity control strategies in several hot-humid cities. Their study included two homes of different efficiency levels with a constant internal moisture generation rate of 4.7 kg/day (10.3 lb/day), lumped moisture capacitance multiplier, cooling set point of 23.9 °C (75°F), and number of occupants. Their study con-

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cluded that explicit dehumidification must be provided to maintain space relative humidity (RH) below 60%, particularly in the higher-efficiency home.

Fang et al. [5] conducted a similar study by investigating three house efficiency levels in a single city. Their study used an internal moisture generation rate of 6.8 kg/day (15.0 lb/day) and had similar assumptions to those made for the research documented in [4]. Fang et al. [5] also concluded that high-performance homes are prone to higher humidity levels compared to typical homes.

A study by Rudd et al. [6] performed numerous simulations in different climates and compared energy use and comfort using a metric of hours above 60% RH. Various inputs to the simulation, including moisture capacitance, internal loads, cooling and heating set points, and duct location, were varied independently and deterministically to evaluate the sensitivity that each variable had on energy use and RH. The study utilized models that could accurately capture moisture evaporation from the cooling coil during the off cycle but used a simple lumped capacitance model for moisture buffering of the building and its furnishings.

Buechler et al. [7] used a probabilistic modeling approach for many of the simulation inputs (e.g., building characteristics, occupancy, occupancy behavior, and thermostat set points) to simulate the indoor climate of residential buildings located across the United States. In their study, they used a single-layer effective moisture penetration depth (EMPD) hygrothermal model in EnergyPlus that is generally more accurate than lumped capacitance methods [8] but then used air-conditioner models that did not model off-cycle evaporation from the cooling coil. Buechler et al. [7] focused on generating a distribution of indoor environmental data for various U.S. climates but did not analyze which input parameters caused the largest variations in indoor climate.

The objective of this study is to achieve improved modeling of indoor humidity through the use of advanced hygrothermal and air-conditioner models and a combination of stochastic and deterministic inputs. This improved approach is used to explore the following objectives:

- Characterizing the sensible and latent loads of typical construction homes and low-load homes to evaluate whether current cooling equipment is capable of meeting the loads
- Evaluating the sensitivity of indoor humidity to variations in internal loads and thermostat set points to better understand how these occupant-driven parameters affect indoor humidity
- Determining the effect that air-conditioner sizing, supply airflow rate, and blower-off delay have on indoor humidity to determine what aspects of equipment selection and setup should be the main focus for equipment installers and service technicians in order to achieve the desired indoor comfort

2. Modeling approach and assumptions

This study uses building simulation software (EnergyPlus version 8.7.0 [9]) to estimate latent and sensible load, indoor humidity, and space conditioning energy use for different climates and house types. The simulations include variation in occupant behavior, moisture buffering levels, and air conditioner sizing and control. Internal loads vary widely due to the number of occupants and occupant behavior. Thus this study takes a stochastic approach to modeling internal loads. This enables us to understand the effect of each of the above without a strong dependence on internal loads, which are occupant driven and can vary considerably. The other building and heating, ventilating, and air-conditioning (HVAC) characteristics are set to one of three levels while the occupant inputs are varied stochastically.

The details of each configuration (building, HVAC equipment, and occupant) are described in the following three subsections. The section concludes with further details on our simulation and analysis methods, including the values used for the low, baseline, and high cases for each characteristic listed in Section 2.4.

2.1. Building model and assumptions

2.1.1. Climates and building types

Of particular interest to this study is how the required cooling sensible and latent loads are changing as building envelopes and building equipment become more efficient. Two levels of house efficiency were examined: standard-efficiency homes based on International Energy Conservation Council (IECC) 2009 requirements [10] (IECC 2009 homes) and high-efficiency homes based on the U.S. Department of Energy (DOE) Zero Energy Ready Home (ZERH) requirements [11] (low-load homes). The house models were climate specific to reflect energy efficiency requirements that vary based on climate zone. Ten cities were selected to cover the range of different climates in the United States, as shown in Fig. 1. Typical meteorological year (TMY) 3 data were used for running the simulations [12].

A two-story, 229 m^2 (2,500 ft^2) home (Fig. 2) with three bedrooms and two bathrooms was used for the study, based on data collected by the U.S. Census Bureau [13]. The house was oriented north, simulated with neighbors located 15 feet to the left and right, and included a garage and an unfinished, vented attic. The foundation type was either a slab-on-grade, unvented crawlspace, or unconditioned basement, which was selected for a particular city based on the most common type in its climate zone found in the U.S. Energy Information Agency (EIA) *2009 Residential Energy Consumption Survey* (RECS) [14].

The Building Energy Optimization (BEopt) version 2.7 software tool was used in developing our simulation inputs [15]. Climate-dependent construction assumptions, such as wall, attic, and foundation thermal resistance, and other building inputs, such as window area distribution and thermal mass, for both homes can be found in [10,11,16]. Exterior cladding for each climate zone was based on [17].

The low-load home was assumed to have a whole-house exhaust fan operating continuously to achieve American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 62.2-2013 total required ventilation rate [18], which was 0.05 m^3/s (104 cfm) for the house geometry chosen for the study, and both homes were modeled with kitchen, bathroom, and clothes dryer spot ventilation based on the internal gain profiles described in Section 2.3.1. Natural infiltration was modeled using the AIM-2 model [19], and infiltration rates for the IECC 2009 and low-load homes were taken from [20] and [11], respectively. The HVAC duct location for the IECC 2009 home was based on the Building America House Simulation Protocols (BA HSP) [16] with slab-on-grade homes having ducts located in the vented attic. Ducts in the low-load home were assumed to be located within the building thermal envelope.

2.1.2. Moisture buffering model

Moisture buffering of building materials impacts the indoor humidity by storing and releasing moisture and reducing or delaying peaks in the indoor humidity. To account for this buffering, we use a two-layer EMPD model, which has been shown to be more accurate than the single-layer version without increasing the complexity of the required model inputs [8]. This model has been shown to accurately represent the daily and weekly buffering of humidity in residential buildings [8,21] and is both more realistic than the commonly used effective capacitance model and much simpler to implement and use than the detailed, but accurate, finite difference approach [8,22].