Interior Moisture Design Loads for Residences

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ABSTRACT

This paper outlines a methodology to obtain design values for indoor boundary conditions for moisture design calculations for residences. This is part of a larger effort by ASHRAE Standard Project Committee 160P, Design Criteria for Moisture Control in Buildings, to formulate criteria for moisture design loads, analysis techniques, and material and building performance. The standard is being developed to provide a consistent framework for moisture analysis and design. The assumptions for boundary conditions can have a large influence on the results of the moisture design analysis of a building, and the choice of boundary conditions may be the most important determinant for design recommendations based on the analysis. This paper focuses on interior moisture design loads for residences and proposes a procedure to estimate the design indoor humidity for both winter and summer conditions. The interior humidity is a function of moisture release, ventilation, dehumidification, and moisture storage in the materials in the building. If the home is not air conditioned or dehumidified, the weekly or monthly average design indoor humidity can be calculated from design ventilation and moisture release. In an air-conditioned home, the situation is more complex. It is difficult to quantify the dehumidification of an air-conditioning system typically controlled by indoor temperature rather than moisture because the cycling frequency of the air-conditioning equipment affects its ability to remove moisture. Although the specific data required for sophisticated calculations that account for changes in moisture removal due to system cycling are not available, this paper will discuss the issues involved and describe simplified alternative approaches.

INTRODUCTION

During the last decade, a number of computer simulation tools were developed to predict thermal and moisture conditions in buildings and the building envelope. In addition to their use as forensic tools in the investigation of building failures, these computer models are increasingly used to make recommendations for building design in various climates. However, results obtained with these models are extremely sensitive to the assumed moisture boundary conditions. For instance, during winter, the moisture conditions in walls depend greatly on the indoor humidity conditions (TenWolde et al. 1995). Thus, a consistent approach to moisture design demands a consistent framework for design assumptions, or assumed “loads.” The question whether or not design features such as vapor retarders or ventilation systems are necessary cannot be answered unless there is a consensus definition of the interior and exterior moisture boundary conditions that the building is expected to be able to sustain without negative consequences to itself or its inhabitants.

No standardized methodology for moisture design exists as yet, but ASHRAE Standard Committee 160P, Design Criteria for Moisture Control in Buildings, is attempting to formulate appropriate design assumptions for moisture design analysis and criteria for acceptable performance. While Geving (2000) summarized the issues and various statistical approaches to the use of models for building design, the 160P committee is trying to arrive at design loads despite a general lack of data and information. The committee is formulating several research projects to obtain better data, and they will recommend these projects for funding by ASHRAE. The stan-

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dard will include interior design loads (temperature, humidity, and air pressure) as well as exterior design loads (temperature, humidity, and rain).

Ideally a design analysis involves the determination of the probability of failure, treating all design parameters and loads as stochastic variables (Geving 2000). However, sufficient data are often not available to make a full statistical treatment practical. Instead, a moisture design protocol will have to be based on a combination of statistical data and professional judgment where only limited data exist. Another judgment involves the choice of an acceptable probability of the occurrence of damage. Although it is common to impose very stringent criteria for structural design because of safety concerns, moisture damage usually occurs over a long period of time and usually has less disastrous, although sometimes costly, consequences. A consensus is beginning to emerge that a 10% likelihood of failure is an appropriate level in building moisture design analysis, and we will use this for the purposes of this paper. The definition of failure will also be addressed in ASHRAE Standard 160P.

In a moisture analysis for building envelope design, the choice of indoor environmental conditions is extremely important, especially for buildings in cold climates. Several European countries have defined Indoor Climate Classes. For instance, Tammes and Vos (1980) describe four climate classes for use in the Netherlands based on interior vapor pressure ranges. This approach requires a different definition for each climate and does not account for large seasonal changes. Sanders (1996) and the IEA Annex 24 take a different approach and define four climate classes on the basis of three critical indoor vapor pressures or "pivot points." These pivot points are related to the occurrence of condensation in a north-facing wall, net annual moisture accumulation in a north-facing wall, or net annual moisture accumulation in a flat roof. These pivot points depend on construction and climate.

In contrast to these approaches, we favor a design indoor climate definition that is based on engineering principles, is independent of construction, and reflects the influence of ventilation and air-conditioning equipment and controls that may or may not be part of the building design. In buildings where indoor humidity and temperature are explicitly controlled, the building envelope performance should be evaluated with the intended indoor design conditions. In residential buildings, indoor humidity is rarely explicitly controlled, and default design assumptions are needed for these buildings.

For winter conditions, the indoor humidity depends on a combination of sources (such as people and foundation moisture) and the building ventilation. In some extreme climates, houses are humidified during the winter. In that case an estimate must be made for this additional moisture generation rate. For summer conditions, there is the added complication of air conditioner and dehumidifier operation for the whole house or individual rooms. Unfortunately, the moisture removal performance of these devices is highly variable and depends on a host of factors that cannot easily be dealt with during the design process. For these reasons, we propose to use a simplified method for estimating indoor humidity during the cooling season that does not require detailed calculation of dehumidifying equipment performance.

DESIGN INDOOR HUMIDITY FOR HEATING

Humidity of indoor air is the result of a balance between moisture gains, moisture removal from the building, and net moisture exchange with hygroscopic materials inside the building. TenWolde (1994a, 1994b) showed that moisture storage in residences stabilizes the indoor humidity, and that daily or even weekly averages can be used for the purpose of building moisture analysis. Ignoring storage and using time-averaged values for the other parameters allows the determination of the indoor vapor pressure:

$$P_i = P_o + \frac{P_{atm} m_s}{0.62198 m_v} \quad (1)$$

where
p_i = indoor vapor pressure, in. Hg (Pa)
p_o = outdoor vapor pressure, in. Hg (Pa)
p_{atm} = atmospheric pressure, in. Hg (Pa)
m_s = moisture source rate, lb/h (kg/s)
m_v = ventilation rate, lb/h (kg/s)

The ventilation rate for residential buildings is often expressed in terms of air changes per hour, rather than as a mass flow rate. The mass flow rate can be obtained from the air change rate using Equation 2:

$$m_v = \frac{\rho VI}{n} \quad (2)$$

where
ρ = air density, lb/ft^3 (kg/m^3)
V = building volume, ft^3 (m^3)
I = air exchange rate, 1/h
n = 1 in IP units, 3600 s/h in SI units

Combining Equations 1 and 2 with the assumption of a standard atmospheric pressure of 29.9 in. Hg (101.3 kPa) and air density of 0.075 lb/ft^3 (1.2 kg/m^3) yields a simple equation.

$$p_i = p_o + \frac{cm_s}{VI} \quad (3)$$

where c = 641 in. Hg·ft^3/lb (4.89×10^5m^2/s^2).

The moisture source term in Equation 1 includes both generation (e.g., people) and dehumidification. If dehumidification exceeds the rate at which moisture is added, this term becomes negative. However, we do not recommend using Equations 1, 2, and 3 when the indoor air is dehumidified. That situation is discussed later in this report.

The design indoor vapor pressure is obtained using design values for outdoor vapor pressure (moisture design weather data), moisture sources and sinks, and ventilation rate. In this paper we do not discuss the issues surrounding the choice of moisture design weather data; instead, we focus on the choice

TABLE 1
Daily Residential Moisture Release

	Daily moisture release (kg/day) per household type			
Source	**1–2 adults**	**1 child**	**2 children**	**3 children**
International Energy Agency (IEA 1991) and Christian (1993)*		10		
			5–10	
				14.4
	7	20		
			14.6	
	13.2	19.9	23.1	
		11.5		
		5–12		
		6–10.5		
	4.3			
TenWolde (1988), home 1	7.2			
TenWolde (1988), home 2	6.8			
TenWolde (1988), home 3	8.5			
TenWolde (1994b), home 1	6.6			
TenWolde (1994b), home 2	5.5			
TenWolde (1994b), home 3	6.6			
TenWolde (1994b), home 4	6.6			
Average	7.2	11.9	13.3	14.4

* Data in IEA 1991 are in Table 6.2, p. 6.5.

of design indoor humidity levels as influenced by building design and occupancy. Equation 1 shows that the indoor vapor pressure varies with weather and the ratio of moisture sources to ventilation rate. A combination of high moisture production and low ventilation rates produces the highest indoor humidity. The selection of moisture source and ventilation rates for design depends on how extreme the indoor conditions for design needs to be. The building moisture research community (as represented by ASHRAE Standard Project Committee 160P) has reached a consensus opinion that, for design purposes, the occurrence of significant moisture problems in 10% of homes at any time during a 10-year period is an appropriate choice for design. This means that, for design purposes, design indoor humidity conditions that are exceeded in 10% of homes should be used in conjunction with weather data of a severity that is exceeded 10% of the time. To obtain a design humidity that is exceeded in 10% of homes, we combined the design moisture generation rate that is exceeded in 32% of homes with a design ventilation rate that is exceeded in 68% of homes (i.e., because 32% of the homes have a lower ventilation rate, the indoor humidity will be exceeded in 32% × 32% = 10% of homes).

Residential Moisture Generation

Data on residential moisture generation vary widely and are difficult to interpret or analyze. The data originate from different authors and were measured under different conditions and climates and in different building construction types. These differences are undoubtedly part of the reason for the wide variation in the data. The most complete summary of data was published in a report of the IEA Annex XIV (IEA 1991) and was reproduced by Christian (1993). The reported average moisture production rate for one to two adults is on the order of 8.2 L/day or 0.75 lb/h. These data can be augmented with data published by TenWolde (1988, 1994b), who reported a measured average of 6.8 L/day (0.62 lb/h) for seven households without children. The combined data are summarized in Table 1.

The average of both of these data sets is about 7.2 kg/day (0.66 lb/h) for one to two adults, with a standard deviation of 2.2 kg/day (0.2 lb/h). If we assume that the data are normally distributed, we can determine that the 32% exceeding level is approximately 8 kg/day (0.7 lb/h), or 9×10^{-5}kg/s. The IEA data also indicate an additional 4 kg/day (0.4 lb/h) for the first child, 2 kg/day (0.2 lb/h) for the second child, and 1 kg/day (0.1 lb/h) for each additional child. For design purposes, it is

TABLE 2
Residential Design Moisture Generation Rates

Number of bedrooms	Moisture generation rate		
1 bedroom	8 kg/day	0.9×10^{-4} kg/s	0.7 lb/h
2 bedrooms	12 kg/day	1.3×10^{-4} kg/s	1.1 lb/h
3 bedrooms	14 kg/day	1.6×10^{-4} kg/s	1.3 lb/h
4 bedrooms	15 kg/day	1.7×10^{-4} kg/s	1.4 lb/h
Additional bedrooms*	+1 kg/day	$+0.1 \times 10^{-4}$ kg/s	+0.09 lb/h

* Moisture generation per additional bedroom.

often assumed that the occupancy is two adults for the first bedroom and one child for each additional bedroom. Thus, residential design moisture release rates can be defined as in Table 2.

The generation rates in Table 2 are identical to the average values published by IEA Annex XIV (IEA 1991). The measured rates already likely include moisture contributions from foundations and other structural sources; therefore, those sources do not need to be added unless there is reason to believe that they will be unusually large.

Residential Ventilation

If the home design includes a designed ventilation system, the expected minimum continuous design ventilation rate should be used for the calculation of design indoor vapor pressure. Ventilation effectiveness should be accounted for according to ASHRAE Standard 62.2P. However, the vast majority of new homes being built do not currently include a mechanical ventilation system. Without a designed ventilation system, a default ventilation rate is needed based on statistical data for new residential buildings. Sherman and Dickerhoff (1998) present such data for U.S. dwellings, which show that the newest homes, built in 1993, had an approximate average normalized leakage of 0.3, with a standard deviation of approximately 0.2. The normalized leakage approximately corresponds with the annual average air exchange rate in air changes per hour (ASHRAE 1997). If we assume a normal distribution, 68% of new homes exceed a natural ventilation rate of about 0.2 air changes per hour (ach). We therefore propose that for purposes of calculating the design indoor vapor pressure (Equation 2), a default design ventilation rate of 0.2 ach be used, unless a designed mechanical ventilation system is included in the home design. The average 1993 home was not designed and built with a continuous air barrier system. If a continuous air barrier system is part of the design, we propose that the default natural ventilation rate should be further reduced to 0.1 ach. However, such specially designed energy-efficient homes typically include mechanical ventilation systems as part of the design.

For houses with natural ventilation (but not mechanically ventilated houses), the ventilation rate increases with lower outdoor temperatures because air pressure differences between the inside and outside are proportional to the difference between inside and outside temperatures. Thus, the highest ventilation rates usually occur in the winter—the time for which we are attempting to estimate the indoor moisture load. This implies that an annual average 0.2 ach may be a conservative choice when it is used in the calculation of indoor conditions during the winter months. If windows and doors are opened during spring and fall, the ventilation rate also increases, and 0.2 ach may again be a conservative choice. However, from a design standpoint, there is no guarantee that occupants will open windows, and there is a growing number of reasons why they would not, such as security concerns and noise.

Example Calculation

The example we will use is a 2,200-ft^2 (204-m^2), four-bedroom home in Madison, Wisconsin, and we will calculate the design indoor vapor pressure for January. The home does not have a designed ventilation system or a continuous air barrier system, so we will use the default ventilation rate of 0.2 ach. The average Madison outdoor dew-point during January is about 9.9°F (–12.2°C), which corresponds to a vapor pressure of 0.0705 in. Hg (240 Pa). The design moisture release rate for a four-bedroom home is 1.4 lb/h (2.1×10^{-4} kg/s). Assuming 8-ft (2.4-m) ceilings, the house volume is approximately 17,600 ft^3 (498 m^3). Thus, the design indoor vapor pressure for January can be calculated (using Equation 3) as

$$p_i = 0.0705 + \frac{641 \times 1.4}{0.2 \times 17600} = 0.325 \text{ in. Hg (1100Pa)} .$$

With an indoor temperature of 70°F (21°C), this translates into a design indoor relative humidity of about 44%, which is a realistic design level for Wisconsin.

DESIGN INDOOR HUMIDITY FOR COOLING

The previous sections did not account for any water vapor removal other than by ventilation with outdoor air. Air-conditioning (AC) equipment and dehumidifiers remove significant amounts of water vapor from the indoor air. For the purposes of design humidity calculations, however, it is difficult to quantify the effect of residential AC equipment because the equipment is typically temperature controlled—not humidity controlled—and the fraction of its total capacity used for humidity control is unknown. Another difficulty with this approach is the effect of cycling on the effective moisture removal rate. During the start-up portion of a cooling cycle, the coil removes little or no water vapor and it is uncertain how long it takes before a typical residential AC unit begins to remove moisture from the air. Because cooling equipment sizing is based on an extreme outdoor design temperature, even a carefully sized AC unit will cycle often on a typical day. If the unit is oversized, the cycling frequency will increase and further reduce the ability of the unit to remove moisture. Because of these complications and lack of information, it

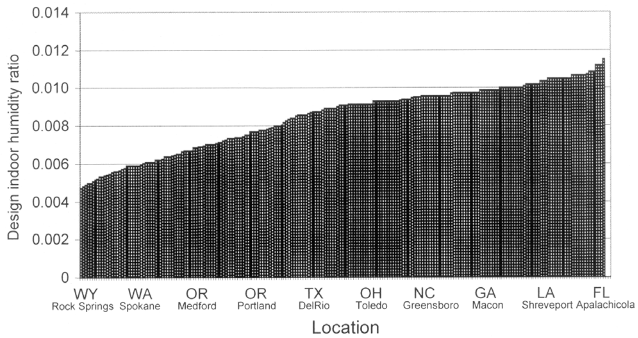

Figure 1 *Design indoor humidity ratios as used in draft ASHRAE Standard 152P.*

proved impossible to devise an engineering-based method to calculate typical moisture removal rates. Until better information becomes available, one alternative is to prescribe a constant design indoor humidity during periods when the AC equipment is operating.

Industry standard sizing methods (ACCA 1986) use the difference between indoor and outdoor moisture at fixed indoor humidity levels—50% or 55% relative humidity (RH) at 75°F (24°C). Similarly, there are calculation methods for selecting the appropriate equipment to use to achieve these conditions (ACCA 1995). These design methods explicitly fix the indoor humidity and assume that the equipment operates properly so as to achieve these conditions. However, this fixed indoor humidity approach has been found to have significant problems. In the development of an ASHRAE standard for efficiency of residential thermal distribution systems (ASHRAE 1999), the project committee found that fixing indoor temperature and humidity conditions gave unrealistic latent cooling loads and resulted in very poor estimates of system efficiency. The project committee found that the indoor conditions need to vary with outdoor conditions, with higher humidities in more humid climates (e.g., Florida) and lower indoor humidities in drier climates (e.g., Nevada). A simple linear algorithm was developed to allow the indoor conditions to vary with outdoor climate. This algorithm also implicitly includes the dehumidification effect of the air conditioner as well as humidity added by indoor sources (e.g, people).

We used West Palm Beach, Florida, as a moist extreme, based on ASHRAE fundamental design data (ASHRAE 1997). This location has a cooling design dry-bulb temperature of 90°F (32°C) and a mean coincident wet-bulb temperature of 78°F (26°C), which translates into an outdoor humidity ratio of 0.018. We used Las Vegas, Nevada, as an extreme dry, hot climate; this location has a cooling design dry-bulb temperature of 107°F (42°C) and mean coincident wet-bulb temperature of 65°F (18°C), with a resulting outdoor humidity ratio of 0.004. We assumed 30% indoor RH for Las Vegas and 50% for West Palm Beach. At a 78°F (26°C) dry-bulb temperature, an RH of 30% gives a humidity ratio of 0.006 and an RH of 50% gives 0.012. Using the two combinations of indoor and outdoor conditions for the two locations, we fit a linear relationship to these data resulting in Equation 4:

$$w_i = 0.004 + 0.4w_o \tag{4}$$

where w_{i} = indoor humidity ratio

w_{o} = coincident design outdoor humidity ratio (cooling)

This algorithm has been applied to 219 locations in the United States and has been found to be extremely robust (i.e., no locations produce unreasonable values for indoor humidity). Figure 1 summarizes the calculated indoor design humidity ratios for these 219 locations. We recommend that Equation 4 be used to estimate indoor humidity for moisture design calculations. This equation can be rewritten in terms of vapor pressures:

$$p_i = 0.004\frac{p_{atm}}{0.62198} + 0.4p_{oc} \tag{5}$$

where p_{i} = moisture design indoor vapor pressure, in. Hg (Pa)

p_{oc} = cooling design outdoor vapor pressure, in. Hg (Pa)

DESIGN INDOOR HUMIDITY FOR DEHUMIDIFICATION

Dehumidification equipment is generally controlled with a dehumidistat, and the intended setpoint should be used to evaluate the building design. However, this only applies if the dehumidification equipment serves the whole house. Most residential dehumidifiers are used in single rooms or areas (e.g., basements) and do not control humidity in the entire house. In that case, it is not possible to devise a simple methodology for calculating design indoor humidity. In the interim, ASHRAE Standard Project Committee 160P will have to devise a way to give appropriate credit for such dehumidification equipment. It may be appropriate to apply the methodology for temperature-controlled AC equipment to room dehumidifiers.

SUMMARY AND DISCUSSION

This paper outlines a methodology to obtain design values for indoor boundary conditions for moisture design calculations in houses. Although the procedures may seem cumbersome, the choice of boundary conditions is too important to leave up to the individual designer or modeler because any predictions of moisture problems in houses are highly dependent on boundary conditions. Different choices could be made and some of the proposed design values are based on judgment rather than adequate information, but it is important that we begin to standardize the approach to moisture design and analysis so that different design considerations can be fairly evaluated.

For heating calculations, a simple steady-state approximation for indoor conditions is presented that allows the indoor humidity to change with outdoor conditions, ventilation rate, and moisture sources and sinks within the house (primarily human occupancy). For cooling calculations, a simple empirical relationship is presented that includes outdoor conditions explicitly but has implied values for sources and dehumidification by air-conditioning equipment. In both cases, a simple approach was taken so that the indoor humidity estimates will be easy for the designer to make and will also be robust and generate realistic values for a wide range of conditions. These factors are most important for general design calculations where different methods of estimating humidity problems and solutions are examined. In particular, these methods will be applied in proposed ASHRAE Standard 160P, Design Criteria for Moisture Control in Buildings.

This paper does not deal with drying of construction materials during the initial occupancy period. We recognize this as an important issue and the cause of a significant number of problems, but the solution lies in adequately drying out the building before occupancy and keeping materials dry on the building site—not in changes in building design. It is difficult to quantify the effect of construction moisture on indoor humidity. ASHRAE Standard 160P is likely to adopt high default values for initial moisture contents of the building materials if no adequate procedures are included for drying in the construction plans.

It is important that the definition of the "loads" provides appropriate choices to the designer. For instance, the definition of design indoor humidity provides the designer with the option to (1) design the building envelope to withstand a potentially high indoor humidity load, (2) include a ventilation system in the design to lower the indoor humidity (of course this option does not work in all climates), or (3) include dehumidification equipment to lower the indoor humidity (although we have not yet found a simple method to appropriately account for the effect of a typical room dehumidifier).

Similarly, it would be preferable to be able to devise a design indoor humidity with air-conditioning that provides appropriate sizing incentives to the designer. The lack of information on the cycling behavior of residential AC equipment and the use of dry-bulb temperature to control equipment operation made it impossible to do so at this time.

This paper deals only with indoor boundary conditions in residential buildings, but residential buildings provide the greatest challenge. Commercial buildings tend to include HVAC equipment that has been designed to provide a certain range of indoor conditions, and, therefore, there should be less uncertainty about the likely range of indoor conditions after the building is in use. An even more important part of the task is the definition of outdoor design conditions. The majority of moisture damage to buildings is caused by rain penetration or other types of water intrusion into the building. The ASHRAE Standard Project Committee 160P is also grappling with that issue.

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