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The need for an accurate indoor humidity model for building envelope performance analysis

F. Tariku & K. Kumaran
National Research Council, Institute for Research in Construction, Ottawa, Canada

P. Fazio
Concordia University, Department of Building, Civil and Environmental Engineering, Montreal, Canada

ABSTRACT: The performance of a building envelope component is usually assessed based on the moisture analysis of individual components (such as cladding, sheathing board and/or drywall) for their drying potentials and likelihood of occurrence of problems associated with high moisture accumulation. In the current building envelope simulation practice, the indoor and outdoor boundary conditions are predefined in the context of the local weather data. The indoor boundary conditions are usually assumed to be constant throughout the simulation period, or two sets of values for the summer and winter periods are assumed. Although the outdoor boundary condition (weather data) is independent of the hygrothermal condition of the envelope, the indoor condition is highly influenced by the building enclosure and occupants' activities. Consequently, simplistic assumptions of indoor humidity profiles, which ignore the dynamic coupling of the indoor environment and building enclosure and represented with a set of empirical values, may lead to inaccurate conclusion about the moisture performance of the building enclosure. In this paper, the effects of indoor humidity profiles that are assumed during moisture performance evaluation of exterior building envelope component are analyzed. The indoor humidity profiles, which are considered in the study, are based on measured and simulated data of a real house. Indoor humidity models including a whole building hygrothermal model are used to generate four indoor humidity profiles. The hygrothermal dynamic responses of the building envelope component with respect to the various cases of indoor humidity assumptions are simulated and analyzed. The simulation results suggest that it is important to have more accurate indoor boundary conditions data, which are based on measurement or whole building hygrothermal modelling, to satisfactorily asses the moisture performance of a building enclosure and potential occupants health problems related to mould growth.

1 INTRODUCTION

The performance of a building envelope component depends on the indoor and outdoor boundary conditions that it is exposed to (Tariku and Kumaran, 2006; Tariku et al. 2007). Thus, establishing boundary conditions that represent the 'real' indoor and outdoor climatic conditions with which the building envelope component performance is assessed is very important. The outdoor boundary conditions are usually well defined based on measured weather data. The weather data that is available for a location can be used for hygrothermal assessment of different building enclosure types that are built in the same location. But the indoor climatic conditions of those buildings can vary depending on the number of occupants, amount of indoor heat and moisture gains, type of interior furnishing, HVAC system and other factors. In fact, the outdoor boundary conditions themselves influence the indoor boundary conditions. Subsequently, the indoor boundary conditions are usually highly variable with time, and are the result of heat and moisture balance of the indoor air. In building performance analysis, assumption of indoor boundary conditions with simple indoor boundary conditions profiles such as constant temperature and relative humidity conditions or one set of values for winter and another set for summer may not be appropriate. The current trend is to use humidity models such as Class model (Sandberg, 1995) or ASHRAE Standard 160P models (2006) to define the indoor boundary conditions. In this paper, the impact of indoor humidity assumptions on the hygrothermal performance assessment of building envelope component is presented.

2 REFERENCE HOUSE INDOOR HUMIDITY

The reference house considered in this paper is an occupied building in Carmacks, which is located in the northwestern part of Canada in Yukon Territories at latitude of 62° 7' north and longitude of 136° 11' west and has an elevation of 543 m above sea level. As part of a NRC-IRC research project (Rousseau et al., 2007) the indoor and outdoor conditions of the house were monitored for four weeks, January 19th to February 20th, 2006. The average outdoor temperature during the monitoring period is –19°C while the indoor temperature is fairly constant at 20°C. In addition to the indoor and outdoor temperature and relative humidity the dimension, orientation, building enclosure components including windows areas and orientations, air-tightness, occupancy and mechanical systems of the house were documented. Based on the available data the indoor humidity of the house is predicted using the Class, ASHRAE Standard 160P and HAMFitPlus (Tariku, 2008) models. Class-model is developed by Sandberg (1995) based on large-scale field survey results. Later on, the model is adopted in the European Standard (EN ISO 13788) to generate the indoor humidity boundary condition that is required in the hygrothermal performance assessment of building envelope components. The house is occupied by five people in the day time and six at night. It has a floor area of 81.9 m^2 and volume of 196 m^3. Based on the occupancy and use of the building the house can be categorized between medium and high classes. The corresponding indoor relative humidity predictions are represented as “Lower bound” and “Upper bound”, respectively, to cover the possible range of values. The ASHRAE Standard 160P Intermediate model takes four important building parameters in consideration; these are: building size (volume), hurly local weather conditions (temperature, relative humidity, wind speed and direction), moisture generation, and ventilation rates. The daily moisture generation rat (16 kg/day) is approximated based on occupant size as per the Standard. While the average ventilation rate, which is calculate by talking account the measured airtightness of the house, building orientation, wind speed and direction, is 0.2 ACH (air-exchange per hour). The only set of data that is required to calculate the indoor relative humidity of the house using the ASHRAE Standard 160P Simple model is outdoor temperature record. The whole building hgyrothermal model, HAMFitPlus, takes into account window condensation and moisture buffering effect of building enclosures in addition to

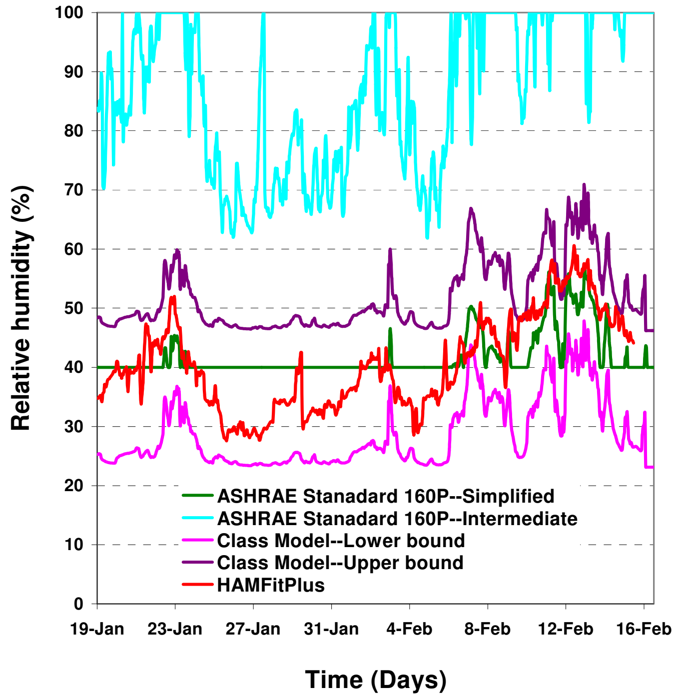

Figure 1 Indoor humidity profiles of a house under consideration generated by various models

the parameters considered in the Intermediate model. The indoor relative humidity predication of these models for the house under consideration and monitoring period (January 19th to February 20th 2006) are presented in Figure 1. As shown in Figure 1 and summarized in Table 1, the indoor humidity profiles obtained from the indoor models considered in this paper vary significantly. The mean predicted indoor relative humidity values of the HAMFitPlus and ASHRAE Standard 160P Simplified models (40.5 and 41.9%, respectively) are close to the corresponding mean measured value (39.8%). The highest and lowest predicted mean relative humidity values are 86.5 and 28.6%, respectively, which correspond to ASHRAE Standard 160P Intermediate model and lower bound of the Class model results, respectively. The minimum indoor relative humidity value predicted by the Intermediate model is 61.8%, which is very high when compared to the actual measured minimum value (23.8%). Moreover, the Intermediate model predicated the highest indoor relative humidity value of 100% while the maximum measured value is 57.3%. HAMFitPlus’s minimum and maximum indoor relative humidity values are 27.6 and 60.6%, respectively, which are close to the corresponding measured values (23.8 and 57.3%, respectively).

Table 1 Statistical summary of the indoor relative humidity values obtained from measurements and numerical models.

	Measured RH values (%)	CLASS Model		ASHRAE Standard 160P		HAM-FitPlus (%)
		Lower Bound (%)	Upper Bound (%)	Simplified (%)	Intermediate (%)	
Mean	39.8	28.6	51.7	41.9	86.5	40.5
Minimum	23.8	23.3	46.4	40.0	61.8	27.6
Maximum	57.3	47.6	70.7	56.5	100.0	60.6

In the following section, the indoor humidity profiles that are generated by the Class model (Lower and Upper bounds), ASHRAE Standard 160P Simple model and HAMFitPlus model are used for hygrothermal performance assessment of a building envelope component. The ASHRAE Standard 160P Intermediate model's prediction, however, is not considered due to its unrealistic and excessive indoor humidity prediction.

3 HYGROTHERMAL PERFORMANCE ASSESSEMENT OF BUILDING ENVELOPE COMPONET

3.1 *Numerical tool*

In this paper, the two-dimensional version of HAMFit (Tariku, 2008 and Tariku et al., 2008) called HAMFit2D is used to simulate the hygrothermal performance of a section of building enclosure. This transient model has the capability of handling the non-linear and coupled heat air and moisture (HAM) transfer processes through multilayered porous media. It takes into account the non-linear hygrothermal properties of materials, moisture transfer by vapor diffusion, capillary liquid water transport and convective heat and moisture transfers. The development and benchmarking of this simulation tool are described in detail in Tariku (2008) and Tariku et al. (2008).

In this model, the set of partial differential equations (PDEs) that govern the HAM transfer across building envelope component are formulated based on building physics. The formulated PDEs are solved simultaneously for air velocity, temperature, and moisture distributions in the computational domain for a given outside environmental condition (weather data) and prescribed indoor conditions using finite-element based commercial software called COMSOL Multiphysics and MatLab. The model is successfully benchmarked against internationally published analytical, numerical and experimental test cases (Tariku, 2008; Tariku et al., 2008).

3.2 *Building component description*

The schematic diagram of this two-dimensional corner section of the house, which is considered for evaluation of indoor humidity profile assumptions effect on building component performance, is shown in Figure 2. The exterior surfaces are covered with sheet metal, which is attached to 12.5 mm thick OSB sheathing board. The wall sections are insulted with 152.4 mm fiberglass insulation. The vapor barrier (Polyethylene sheet), which is installed behind the 12.5 mm gypsum board, is assumed to be continuous. The hygrothermal properties of the OSB, insulation, gypsum board and spruce are taken from the ASHRAE Research project RP-1018 *'A Thermal and Moisture Transport Database for Common Building and Insulating Materials'* (Kumaran et al., 2002). The moisture storage capacity, heat capacity, liquid permeability and thermal resistance of the polyethylene sheet are assumed to be negligible. Its vapor permeability value, however, is taken from ASHRAE Fundamental (2005). For modeling purpose, the thermal and moisture transfer properties of the sheet metal are replaced with the respective equivalent surface resistance coefficients. The absorptivity and emissivity of the exterior surfaces are estimated to be 0.40 and 0.60, respectively.

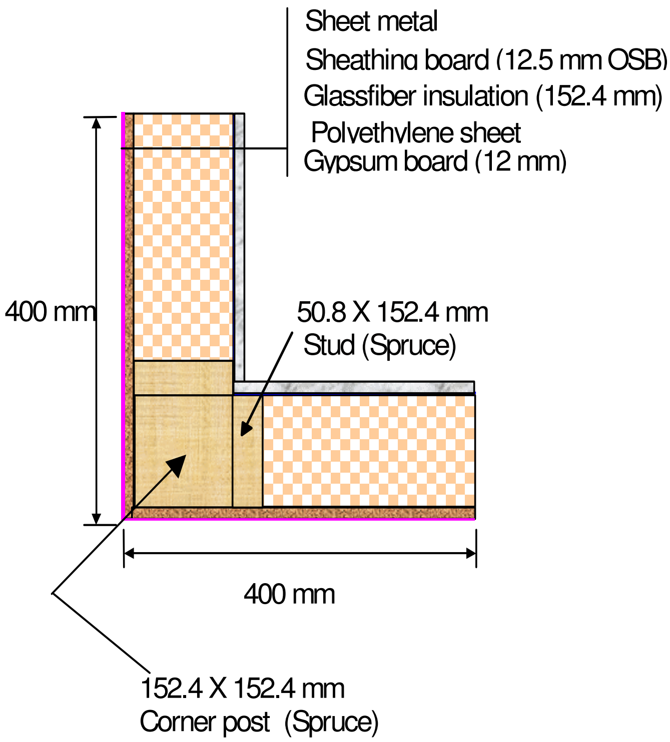

Figure 2 The schematic diagram of two-dimensional corner section that is considered for hygrothermal performance analysis.

3.3 *Boundary conditions*

The hygrothermal simulations are carried out for the same period for which the indoor humidity profiles are predicted (January 19 to February 16, 2006). The computational domain of the corner section is descritized into 1920 quadratic elements, Figure 3. To control the overall mesh density (avoid excessively small and/or large number of elements) each layer is meshed independently, but in conformity with the other. This procedure is necessary due to the high variation in the thickness of the layers, for instance the insulation is about 1000 times thicker than the thinnest layer (Polyethylene sheet). The boundary conditions that are applied on all surfaces are Neumann type boundary conditions, where moisture and heat fluxes are used instead of surface temperature and relative humidity conditions (Dirichlet type boundary conditions). For surfaces A-F and C-D, shown in Figure 3, adiabatic/closed boundary conditions (zero flux) are assumed for both heat and moisture transfers. This is based on an assumption that the temperature and moisture gradients in the lateral directions of the walls become negligible at the mid section of a cavity, 400 mm from the corner point. The heat and moisture fluxes at the interior surface of the domain (D-E-F) are calculated from the indoor climate data, which are determined in Section Figure 3 by the respective humidity model, and using heat and moisture transfer coefficients. The heat transfer coefficient of the two-dimensional corner surfaces is estimated to be 6 W/Km^2 (Sanders 1996, IEA Annex 14 1991). The moisture transfer coefficient of the corresponding surface is 2E-8 s/m, which is estimated based on Lewis relation (ASHRAE Fundamental 2005). The heat transfer coefficient accounts for both convection and long-wave radiation heat exchanges. The external surfaces (A-B-C) are exposed to the local weather conditions. Figure 4 and Figure 5 show the outdoor temperature and relative humidity that are recorded during the monitoring period.

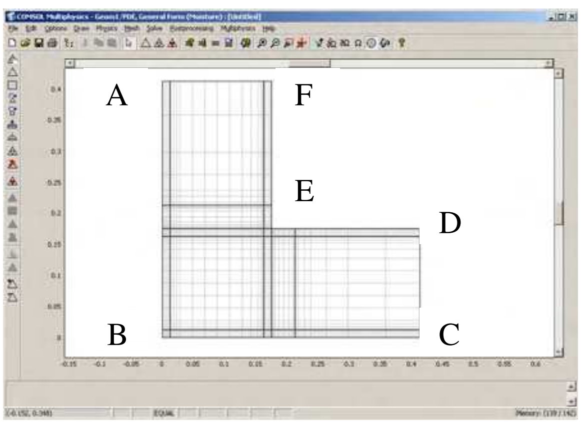

Figure 3 Quadratic mesh of the corner section

Since the exterior layers are metal sheets, wind-driven rain load and moisture exchange with the surrounding is zero. Consequently a zero-flux condition for moisture exchange is assumed for these external surfaces. The effective heat flux on these boundary are calculated by adding the heat gain due to solar radiation and the net heat exchange between the surfaces and the surrounding environment due to long-wave radiation and convective heat exchange mechanisms. For these external boundaries, the convective and longwave radiation heat exchanges are treated independently. The convective heat transfer coefficient depends on wind speed, and approximated by Equation (1) (Sanders 1996). The long-wave radiation heat exchange is estimated based on European Standard prEN ISO 13791 (2004), Annex E.

$$h_c^o = 5.82 + 3.96\,V \qquad V \le 5\ m/s \qquad (1)$$
$$h_c^o = 7.68\,V^{0.75} \qquad V > 5\ m/s$$

where V is the wind speed measured at 10 m 'adjacent' to the house.

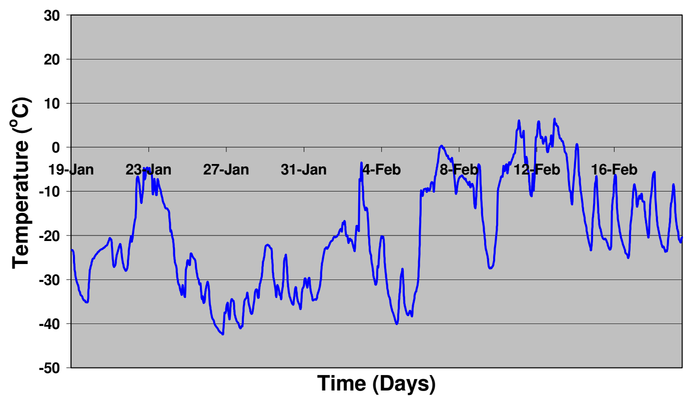

Figure 4. Measured outdoor temperature

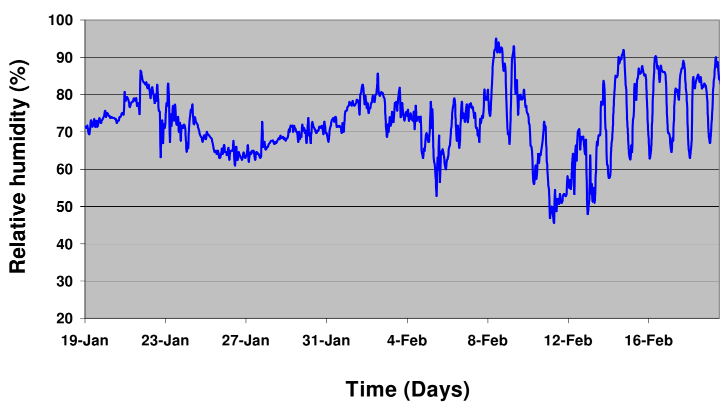

Figure 5 Measured outdoor relative humidity

4 SIMULATION RESULTS AND DISCCUSION

This building envelope section is relatively cold as a result of the thermal bridge that is created by the corner post (152.4 X 152.4 mm) and studs (50.8 x 152.4 mm). Figure 6 shows the typical temperature profile of the corner section of the house on January 29^{th}, 2006. On this particular date, the daily average outdoor and indoor air temperatures were –40.4°C and 17.5°C, respectively. Observation of the temperature profile suggests that the coldest spot on the interior gypsum is a region around the junction of the two perpendicular gypsum boards. Similar temperature profiles are observed in all four simulation cases where the Lower bound (Class model), HAMFitPlus, ASHRAE Standard 160P Simple model and the Upper bound (Class model) indoor humidity profiles are used. This is expected since the indoor temperature is the same in all four cases. But the moisture distributions on the back of the gypsum board, more specifically at the region of interest, are quite different. The moisture distributions across the corner section of the house at the time that corresponds to the temperature profile presented are shown in Figure 7 to Figure 10. In these figures the moisture distributions are represented in terms of relative humidity, and plotted in the same scale for comparison purpose. At this particular time, the daily average indoor relative humidity as predicted by the Lower bound (Class model), HAMFitPlus, ASHRAE Standard 160P Simple model and the Upper bound (Class model) are 25, 34, 40 and 48%, respectively.

In all the four cases the moisture profile in the OSB and insulation layers does not change. This is because these layers do not exchange moisture neither with the internal nor external environmental conditions as they are sealed with polyethylene and metal sheets in the interior and exterior surfaces, respectively.

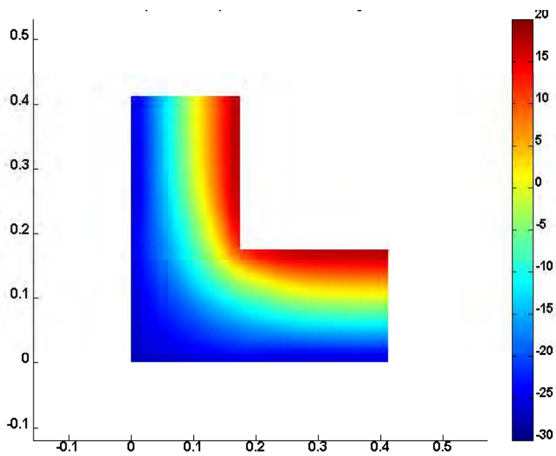

Figure 6 Temperature profile of the corner section of the house on January 29^{th}

But, the gypsum board dynamically interacts with the corresponding indoor environmental conditions. As can be seen in all four relative humidity profile plots, the gypsum at the junction region experiences elevated moisture accumulation compared to the corresponding adjacent gypsum section. The figures also show various degree of moisture accumulation (at the junction region) for the four indoor humidity profiles used. The corresponding relative humidities are: 56% (Lower bound of Class model-Figure 7), 73 % (HAMFitPlus model-Figure 8), 94% (ASHRAE Standard 160P Simple model-Figure 9), and finally 96% (Upper bound of Class model-Figure 10). The implies that the relative humidity at the junction region can vary from 56 to 96% depending on the indoor humidity profile that is assumed for the house under consideration. This wide range of simulation results reinforces the need for accurate determination of indoor humidity that can be used as indoor boundary condition in the analysis of building envelope components performance.

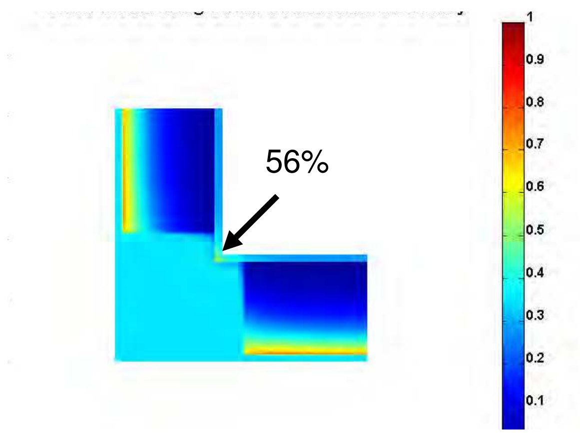

Figure 7 Relative humidity profile of the corner section using indoor humidity profile generated by Lower bound of Class model

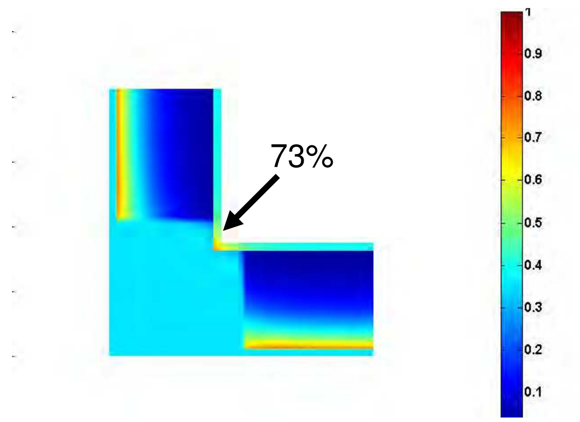

Figure 8 Relative humidity profile of the corner section using indoor humidity profile generated by HAMFitPlus

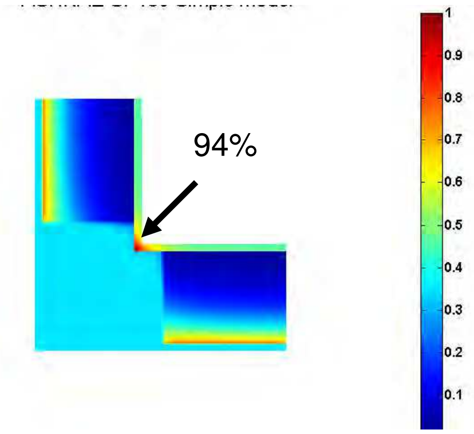

Figure 9 Relative humidity profile of the corner section using indoor humidity profile generated by ASHRAE Standard 160P Simple model

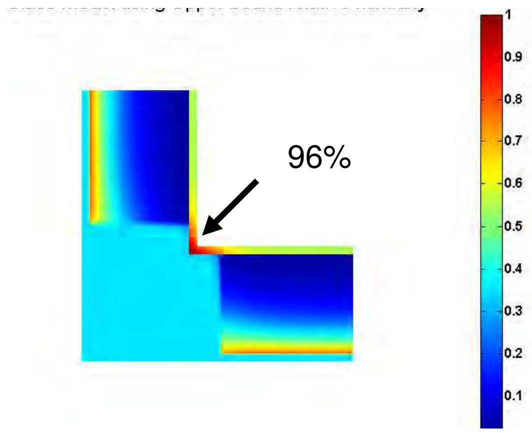

Figure 10 Relative humidity profile of the corner section using indoor humidity profile generated by Upper bound of Class model

Figure 11 shows the temperature time history of the outermost junction point of the two joining gypsum boards. The temperature of this location varies between 2.4°C on January 29th and 15.7°C on February 12, 2006. Generally, it is believed that temperature over 0°C creates a favorable condition for mold growth if accompanied with high relative humidity for long enough time (Viitanen and Salonvaara, 2001). Accordingly, this critical location satisfies one of the criteria for mold growth. The relative humidity profiles of the same critical location as exposed to the four indoor humidity conditions are shown in Figure 12.

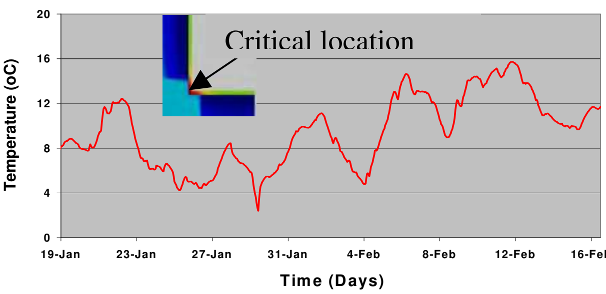

Figure 11 Temperature profile at the rear junction point of the two gypsum boards

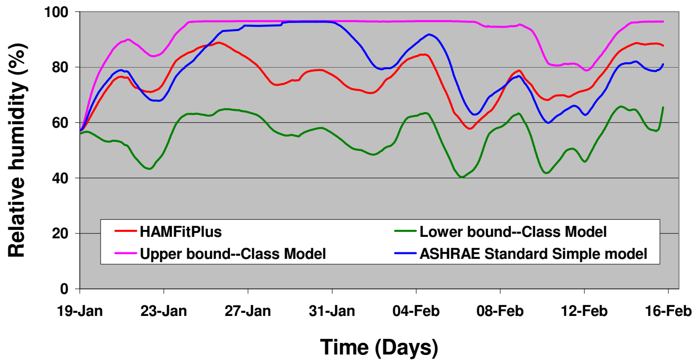

Figure 12 Relative humidity profiles at the rear junction point of the two gypsum boards

The hygrothermal simulation results suggest that the amount of moisture accumulation in the corner gypsum depends on the type of indoor humidity model used to generate the indoor boundary conditions. The combination of the cold outdoor temperature, which promotes condensation, and the higher indoor humidity predicted by the Upper bound (Class model) brings the relative humidity profile of the corner piece to a high level. In the simulation case where the indoor humidity predicted by the Lower bound (Class model) is used as an indoor humidity boundary condition, the same location experiences the lowest level of moisture accumulation. For most of the simulation period, the moisture profiles of the critical point in cases with HAMFitPlus and ASHRAE 160P Simple models are close to each other, and lie more or less in the middle of the Upper and Lower bounds (Class model) results. Their deviations are pronounced for about a week (26th of January to 2nd of February) when the ASHRAE Standard 160P Simple model over predicted the indoor humidity level. At this time the HAMFitPlus indoor relative humidity prediction reaches its lowest value of 23% due to the high ventilation rate that is caused by the relatively cold outdoor temperature, while the ASHRAE Standard 160P Simple model maintains the lower cutoff value of 40%. In general, the relative humidity of the critical point during the entire simulation period is less than 80% in the case of Lower bound (Class model) and 90% in the case of HAMFitPlus. In Table 2 the percentage of time at which the relative humidity of the corner piece is over 80 and 90% in the four indoor humidity models considered are presented. As shown in the table, the critical location experiences a relative humidity over 90% for 70 percent of the simulation period in the case of the Upper bound (Class model) and 26% of the simulation period in the case of the ASHRAE Standard 160P Simple model. The percentage of time in which this critical location has a relative humidity over 80% are 93, 47 and 30% for cases with the Upper bound (Class model), ASHRAE Standard 160P Simple model and HAMFitPlus, respectively. The average relative humidity of the

Table 2. The percentage of time for which the critical location attains a relative humidity over 80 and 90%.

Relative humidity (%)	CLASS Model		ASHRAE Standard 160P Simplified (%)	HAMFitPlus (%)
	Lower Bound (%)	Upper Bound (%)		
> 80	0	93	47	30
> 90	0	70	26	0

critical point for the cases with Upper bound (Class model), HAMFitPlus, ASHRAE Standard 160P Simple model and Upper bound (Class model) are 56, 76, 78 and 90%, respectively. Vittanen and Salonvaara (2001) suggested that a gypsum board with relative humidity over 80% might create a favorable condition for mold growth. If one uses this relative humidity threshold as a measure of building envelope performance, the use of one or the other indoor humidity profiles that are generated by the various indoor models may yield different conclusions about the hygrothermal performance of the building envelope component. For instance, in the cases considered here, the gypsum board can be assessed as it is at high mold growth risk (if one used the Upper bound Class model) or no risk (if one uses Lower bound Class model). As these simulation results suggest, it is very important to use a more accurate indoor model, which is based on whole building heat and moisture balance, to generate the indoor humidity profile that will be used as boundary condition in the hygrothermal performance analysis of building envelope components.

CONCLUSION

In this paper, the impact of indoor humidity assumptions on the hygrothermal performance assessment of building envelope component is presented. The indoor humidity profiles of an occupied building that are generated using different indoor humidity models including Class model, ASHRAE Standard 160P models and a whole building hygrothermal model, HAMFitPlus varies significantly. Subsequent use of one or the other model for hygrothermal performance assessment of a building component yields different moisture accumulation in the critical element of the building envelope section under consideration. As illustrated in this paper, incorrect assumption of indoor humidity profiles lead to inaccurate conclusion about the moisture performance of the building enclosure. Thus, it is very important to use a more accurate model, which is based on whole building hygrothermal analysis, to generate the indoor humidity profile that will be used as an indoor boundary condition in the hygrothermal analysis of building envelope components.

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