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Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

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ABSTRACT

A whole building hygrothermal model has been developed on the basis of an existing detailed model for thermal simulation of buildings. The thermal model is a well-proven transient tool for hour-by-hour simulation of the thermal conditions in multizone buildings. The model has been expanded with new capabilities for transient simulation of indoor humidity conditions, taking into account the moisture buffer capacity of building components and furnishings and the supply of humidity from indoor activities. Also integrated in the model are transient calculations of the moisture conditions in the layers of all the external building envelope components.

The advantage of the new model is that both the boundary conditions for the envelope and the capacity of building materials to buffer the indoor humidity are considered in the same calculation. The model considers the latent heat effect associated with the absorption or evaporation of moisture, and it takes into account the way in which moisture in the building materials affects their thermal conductivity.

The paper presents the principles for the model and some applications and calculation results.

The model is validated against experimental data from a full-scale test cell. In the test cell, it is possible to control the release or withdrawal of humidity from the indoor space and measure the response in humidity of the air and the moisture content of building materials in the room. A sequence of experiments has been conducted using different interior materials to provide source data for the effect of moisture absorption and release. Examples of comparisons between simulated and measured data are presented.

INTRODUCTION

Humidity in indoor spaces is one of the most important factors influencing indoor air quality. Many health-related problems in the indoor environment (e.g., sick building syndrome [SBS] can be associated with high indoor humidity and "damp buildings" [Clausen et al. 1999]). The humidity level in a building depends on a combination of factors such as moisture sources, ventilation and air movement, reservoirs and sinks, heating, insulation, external conditions, as well as building materials and occupants. Among these, the moisture buffering effect of the materials in a building is an important factor. There is a general interest in exploiting the moisture buffering effect of building materials, such as wood, to dampen the cyclic excursions of indoor humidity. However, this effect is often disregarded by building designers and engineers.

Ventilation with fresh air is a way to improve the problems of high indoor humidity, but ventilation requires energy to condition the air and to run the fans of the ventilation systems. So there is interest in being able to design buildings for a suitable balance between moisture supply and required ventilation. However, the humidity condition of indoor air is not just a result of moisture supply from current activities and the actual ventilation rate. It also must be considered that many building materials and interior furnishing are hygroscopic, so they act as buffers for the indoor humidity.

Several approaches to model the indoor humidity conditions have been developed in previous research. The approaches vary from simple steady-state models that completely disregard the indoor moisture buffering (Loudon 1971), over empirical models that acknowledge but physically do not describe the buffering effect (Tsuchiya 1980), to more

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physics-based models that consider the buffering in a surface layer of the building elements (e.g., the effective penetration depth models by Kerestecioglu [1990] and Cunningham [1992]). Furthermore, two different moisture balance models are implemented in version 15 of the TRNSYS simulation system—the effective capacitance humidity model and the buffer storage model (Klein et al. 2000). Typically, previous models have predicted the indoor humidity without consideration of the materials in the deeper layers of building constructions and furnishing, although they set the boundary conditions for the indoor humidity variations.

In contrast, several detailed models have been developed for the moisture conditions of exterior building envelope constructions. High indoor humidity is among the most important reasons for harmful accumulation of moisture in the building envelope, and it can be a direct or indirect reason for extra heat flow though the enclosure of buildings. This has been realized in an international research project—heat, air, and moisture transport in insulated envelopes (HAMTIE), IEA ECBCS 24—where one subtask was devoted to describe the indoor and outdoor climatic influence on the envelope (IEA 1996a). Another subtask of the same project dealt with calculation methods to predict the moisture conditions within the envelope structures (IEA 1996b). The calculation methods all assumed the indoor climate to be prescribed as one of the preconditions for the calculations, disregarding the influence that building components have on the indoor humidity.

It is only recently that models have been developed that make detailed and integrated prediction of both the indoor humidity and the moisture conditions in constructions. Hagentoft (1996) presented an unpretentious model that calculates the moisture conditions both in building constructions and in an indoor zone. Kurnitski and Vuolle (2000) have constructed a transient model for heat, air, and moisture conditions in building envelopes in a modular simulation environment where room moisture and temperature balances are also calculated. A recent development has been made to complement the DOE EnergyPlus program (Crawley et al. 2000) with whole building moisture calculations. However, EnergyPlus is based on a response factor method, which may not have been optimal for calculating transient moisture transfer, as this is a nonlinear phenomenon (Liesen and Pedersen 1999). Finally, a model for calculation of indoor air conditions has been developed from an existing tool for moisture analysis of building envelope parts (Simonson and Salonvaara 2000).

Moisture conditions cannot be predicted without knowing the thermal conditions. It is quite obvious, therefore, to develop a model for prediction of whole building moisture conditions as an extension to an existing model for a detailed thermal analysis of buildings. Such a model already predicts the thermal condition of the indoor environment and all the adjacent building components. Normally, the thermal calculation models are rather elaborate themselves, their thermal predictions have already been validated, and they may have extensive user interfaces. One such model is included in an existing tool for integrated building simulation (Wittchen et al. 2000).

There is a great need to experimentally verify the predictions of whole building hygrothermal models. Some relevant experimental investigations are reviewed by Mitamura et al. (2001) and by Virtanen et al. (2000). In this paper, we describe an experiment using a full-scale test cell to investigate the moisture buffering effect of building materials. The results are used both to characterize the buffering capacity of different materials and to verify predictions of the numerical model. The term “moisture buffering effect” will be used to indicate the ability of building materials to decrease humidity variations in indoor spaces.

NUMERICAL MODELING

The Integrated Simulation Tool

The integrated building simulation tool used for the humidity calculations described in this paper is a computational design tool that comprises models for analysis of indoor climate, energy consumption, and daylight performance of buildings**.** The core of the system is a common building data model, shared by the design tools, and a common database with typical building materials, constructions, windows, and doors. Figure 1 illustrates the integrated simulation tool.

The following computational analyses can be made on most buildings using the integrated simulation tool:

- heat gains from solar radiation, people, lighting, and equipment
- solar radiation through windows
- heating, cooling, and ventilation
- power and energy balance
- steady-state moisture balance (not considering moisture buffering)
- temperature conditions

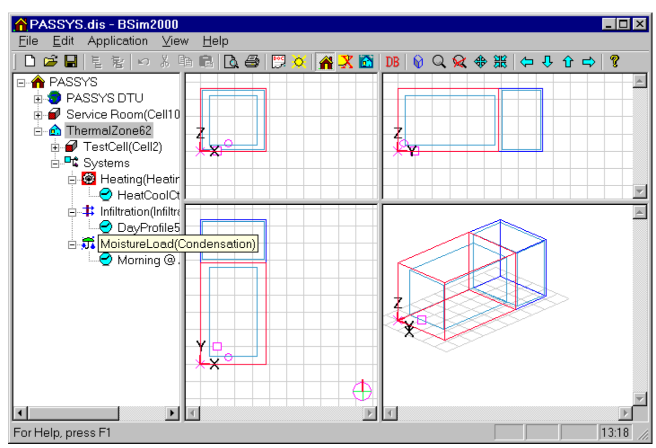

Figure 1 *Graphical user interface of the integrated simulation tool showing the model of the test cell from which experimental data will be used to compare against model predictions.*

- heat and air exchange between zones
- shading conditions
- variable infiltration and venting
- several different ventilation systems simultaneously
- surface temperatures and condensation risk at interior surfaces
- air exchange in connection with infiltration and opening of windows
- air exchange between rooms
- heat and refrigeration recovery in ventilation plants
- supply and exhaust air temperature in ventilation plants
- power from heating and cooling coils in ventilation plants
- humidification in ventilation plants

Whole Building Moisture Model

A transient moisture model for the whole building—its indoor climate and its enclosure—has been developed as an extension to the other models in the integrated simulation tool. A building is seen by the simulation tool as a number of zones, separated from each other and from the outside by constructions of different kinds. A humidity balance is set up separately for each zone. The balance equation expresses that humidity is exchanged by infiltration, ventilation, and air change with the outdoor air and with adjacent zones. Furthermore, humidity is exchanged by convection between air in the zone and the adjacent constructions, and moisture is released to the zones as a result of activities in the zone. The balance equation is dynamic, so it takes into consideration the buffer capacity of the zone air.

In a one-step iterative fashion, the model also integrates calculations of transient moisture conditions for all interior and exterior constructions of the building. The zones facing the constructions give the boundary conditions for the constructions. The iteration within one time step is: (1) calculate the heat and humidity balance for the zones, (2) make the transient heat and moisture calculation for the constructions, and (3) refine the heat and humidity balance for the zones.

Discretized Model of a Building. A building may consist of an arbitrary number of zones and constructions. Every zone is delimited by an arbitrary number of surfaces. In the description of the building, the zones are represented by one node point for which information is held about the temperature, T, and the humidity ratio of the air, x. The air in a zone is considered as being fully mixed, or it is possible in the model to approximate the stratification in the zones.

The constructions consist of one or more layers of building material that are characterized by their thickness and by their properties for heat and moisture transport and accumulation. The layers are subdivided further into one or several control volumes. The node point is always located in the center of the control volumes, and there are node points placed on the two surfaces of the construction. Furnishings may be considered as interior building constructions that face the same zone on both sides or are calculated from one side to an adiabatic vapor-tight center.

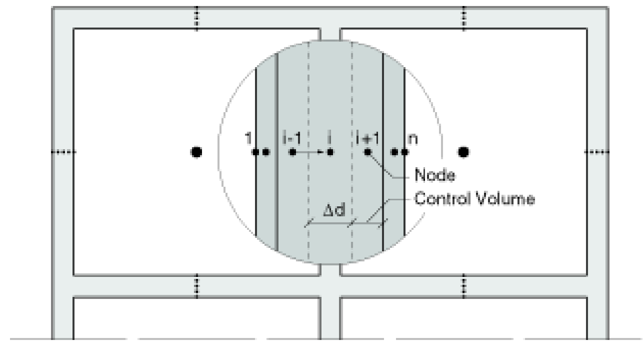

Figure 2 *Part of a plan of a building as understood by the integrated simulation tool with two of its zones and an enlarged view of a wall that separates the two zones. The figure indicates the location of node points for the numerical calculation.*

A simplified plan of a part of a building with several zones is shown in Figure 2 with indication of the discrete node points.

In each time step, calculations of the temperature conditions in the constructions and zones are carried out first before calculating the moisture conditions, so the distribution of the saturation vapor pressure, p_s (a unique function of temperature), is known at the new time level. The same node points and control volumes are used for the thermal as for the moisture calculations.

Humidity Balance for Zone Air. The following influences on the humidity condition of the air are considered:

- humidity transfer from adjoining constructions
- contribution of humidity from various sources and activities (e.g., person load, laundry and drying, bathing, cooking, industrial processes, humidification/drying, and other)
- penetration of humidity from outdoor air (by infiltration and venting)
- supply of humid air from ventilation systems
- humid air transferred from other zones

The humidity balance for zones is made up for the humidity ratio x (mass of water vapor per mass of dry air). The time dependency of changing the moisture content of the air is also taken into account. The moisture balance equation can be expressed as

$$V \cdot \rho_{air} \frac{x^{new} - x^{old}}{\Delta t} = \sum G , \qquad (1)$$

where ΣG on the right-hand side represents the sum of moisture sources in a zone. The equation could potentially lead to inaccuracies because of the time discretization if Δt is large, but in practice the risk is limited because excursions of x are restricted by humidity ratios in the adjacent environments (see the following three equations) and, furthermore, the user has an option to set the level for Δt. Characteristic groups of moisture sources are described in the following.

The humidity transferred between the surfaces of the constructions and the zone air is governed by the convective mass transfer coefficients and is calculated from

$$G_{constr} = \sum_{constructions} A_{surf}\beta(p_{surf} - p_{air}) . \quad (2)$$

The air supplied to the zone may come from four different types of systems: “mixing” (from other zones), infiltration from outside, venting, and (mechanical) ventilation. The supplied air brings humidity with it and, when full mixing is assumed, it suppresses air from the zone with the same humidity ratio as the bulk of the zone air. The moisture added to the zone by ventilation is calculated by summation for all air sources as

$$G_{vent} = \sum_{air\ sources} n_{vent} V \rho_{air}(x_{vent} - x_{air}) , \quad (3)$$

where x_{vent} is the humidity ratio of the air as it enters the zone either from the outside or from another zone, and n_{vent} is the associated air change rate. The summation on the right-hand side of Equation 3 indicates that there may be several air sources.

Furthermore, moisture may be added to the zone air from people or from other moisture loads in the zone. These influences on the humidity of the air may vary according to defined schedules or various control strategies. For instance, moisture loads from people will simply be indicated by a schedule that characterizes the presence and activity of occupants. The humidity contributions from such sources will be collected in a single quantity called G_{syst}.

Now, the total humidity balance for the zone can be made up by inserting the different moisture contributions, G, in Equation 1. After separating the yet unknown, or *new*, conditions on one side of the equation and the known, or *old*, conditions on the other, the following results:

$$x_{air}^{new}\left(1 + \frac{\Delta t}{V\rho_{air}} \sum_{constr} A_{surf}\beta \frac{P}{x_{air}^{old} + 0.622} + \Delta t \sum_{air\ sources} n_{vent}\right)$$
$$= x_{air}^{old} + \frac{\Delta t}{V\rho_{air}} \sum_{constr} A_{surf}\beta p_{surf} + \Delta t \sum_{air\ sources} n_{vent} x_{vent} + \frac{\Delta t}{V\rho_{air}} G_{syst} \quad (4)$$

As an approximation, the value x_{air}^{old} for the vapor content in the previous time step has been used in the recalculation between humidity ratio and vapor content of air on the left-hand side of the equation.

Moisture in Constructions. A finite control volume method is used for the calculation of moisture transfer in the building materials of interior and exterior walls. The finite control volume method is found to be suitable to handle the nonlinear moisture transport phenomena that are caused by moisture-dependent transport and retention properties.

The model for moisture transport in the constructions considers moisture transport in the form of vapor diffusion. Humidity is exchanged with the indoor and outdoor climates as convection of vapor over the surfaces, and there is no possibility for the moment to consider moisture sources such as wind-driven rain or other influences of liquid moisture. The moisture transport internally in the constructions is described in a transient way by considering the moisture buffering capacity of each layer. In this way, it is possible to calculate the risk of condensation or build up of high humidity levels in the constructions. The model takes into account the movement of moisture in the heat balance of the building elements, e.g., the transfer of latent heat that follows the evaporation and condensation processes.

A calculation is carried out for each control volume and time step of the balance between moisture gained and lost by vapor diffusion. The sum of these contributions causes a change of the moisture content from one time step to the next. Using the sorption curves of the materials, the new moisture contents can be recalculated into new relative humidity and vapor pressures. For the sake of numerical stability in all situations, the model uses an implicit calculation procedure based on vapor pressure as driving potential. Despite the numerically stable procedure, the program proposes a time step corresponding to Fourier numbers both for the moisture and heat transports of not more than 1.25 for any of the control volumes in the model. This is in order to minimize inaccuracies because of the time discretization and can be overruled by the user.

Vapor diffusion into a control volume i from the adjacent element i-1 is calculated from Fick's law. The control volumes may be made of different materials with individual water vapor permeability, and the control volumes may have individual thickness. The vapor flux over the interface between the two control volumes in the time step from time index j to $j+1$ is expressed as

$$g_i^{j+1} = -\frac{p_i^{j+1} - p_{i-1}^{j+1}}{\frac{\Delta d_{i-1}}{2\delta_{i-1}} + \frac{\Delta d_i}{2\delta_i} + Z_i} , \quad (5)$$

where Z_i is a possible vapor diffusion resistance *between* control volumes, e.g., representing a thin membrane or a coating of paint. The vapor permeability, δ, is determined for each control volume as a function of local moisture content.

Vapor fluxes, such as that calculated in Equation 5, are used in the moisture balance of the control volumes over the time step Δt, which, for volume i, can be expressed as follows:

$$\rho_i \Delta d_i \frac{u_i^{j+1} - u_i^j}{\Delta t} = -(g_{i+1}^{j+1} - g_i^{j+1}) \quad (6)$$

As indicated by the time index j+1 for the vapor pressures and fluxes in Equations 5 and 6, the procedure is implicit, i.e., set up on the basis of yet unknown vapor pressures by the end of the time step. The equations for all i are dependent on one another, and the moisture transport (5) and balance (6) equa-

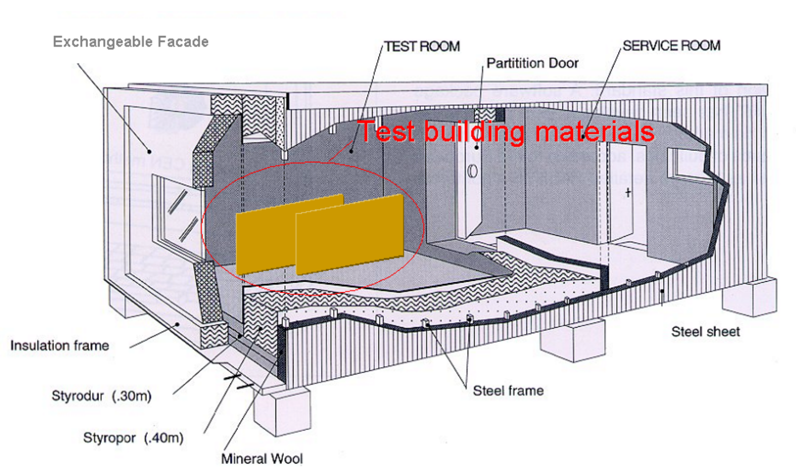

Figure 3 *Isometric view of PASSYS cell.*

tions need closure by coupling the moisture content and vapor pressure through the sorption curves of the materials. How this is solved in the new moisture model of the integrated simulation tool is shown in more detail by Rode et al. (2001).

EXPERIMENTAL VERIFICATION

Experiments

Test Cell and Equipment. An airtight and highly insulated outdoor steel chamber was used with an indoor area of 13.8 m^2 and room height of 2.75 m, giving a volume of 38.0 m^3. This cell was originally constructed for use in an extensive research project, PASSYS, during 1986 to 1993 (European Commission 1994). The walls, roof, and floor of the cell are of sheet steel both on the inside and on the outside, and they are insulated with some 40 to 50 cm of polystyrene and mineral wool. The wall on the southern facade is exchangeable, and the current wall consists of 11 cm of brickwork, 30 cm of mineral wool, and pressure-equalized wood panels on the outside. The wall is covered on the inside with polyethylene foil so as to provide a vapor-tight and nonabsorbing interior surface. An isometric view of the PASSYS test cell is shown in Figure 3.

The cell has an air change rate of about 0.20 h^{-1} at 50 Pa pressure difference. Without pressurization, it is about 0.007 h^{-1} (measured with tracer gas using the decay method).

In the northern end of the test cell is an 8.6 m^2 service room containing the cooling and control systems. Within the test room of the cell is an air distribution system connected to the cell's heating and cooling coils. The cell is instrumented with sensors for measuring both the outdoor climate (three components of solar radiation, ambient temperature, relative humidity, and external surface temperature) and the indoor conditions (air temperatures, surface temperatures, heating, power used by the cooling system and fans, heat fluxes, air infiltration rate, and air velocity). The indoor relative humidity is measured with capacitive moisture sensors with an accuracy of about ±2% RH. The data acquisition system is located in an adjacent building, from which the test cell could be controlled.

To measure the moisture buffering effect of materials, the room was subjected to controlled moisture variations. Rather than controlling the test cell's relative humidity and noting the reaction in the material, the moisture production was controlled, and the resulting RH variation was registered. The idea was to mimic the exposure of building materials in a common indoor climate, but in a controlled way. The principle has been used previously by Padfield (1998) in small (0.5 m^3) test chambers in the lab. The objective of making such tests in the PASSYS test is to make full-scale experiments and to have the possibility of future non-isothermal tests, e.g., with a naturally varying indoor climate caused by solar gain.

Indoor humidification was created by evaporation of moisture from a reservoir of water heated by an electric element. Humidity was withdrawn from the air by a dehumidifier draining into the same reservoir. The water reservoir was weighed with a load cell, and the control system made it possible to control the rates of humidification and drying according to a predefined schedule. The range and accuracy of the load cell was 10 kg±3 g. A schematic diagram of the apparatus is shown in Figure 4. By using the apparatus, it was possible by evaporation of water to imitate in a controlled way the production of humidity in an inhabited room. With the dehumidifier, it was possible to imitate the removal of humidity from the room that would normally take place by ventilation.

Experimental Building Materials. Building materials used in the experiment were plasterboard, chipboard, cellular concrete, plywood, and wood panels. The materials were used in their raw form without paint or wallpaper. These test materials were exposed in turn as the only materials in the cell. The edges of each material were sealed with vinyl tape, so only the plane surfaces of the materials were exposed to the air. The test materials stood vertically in racks on the floor during the experiments. The area and some properties of the test building materials are listed in Table 1. The reason that the areas of each material were different was to obtain about the same variation

TABLE 1
The Tested Building Materials

Test Material	Area (m^2)	Thickness (m)	Density (kg/m^3)	Vapor Permeability (kg/[m·s·Pa])
Plasterboard	13.50	0.013	735	$25 \cdot 10^{-12}$
Chipboard	8.93	0.018	911	$4.5 \cdot 10^{-12}$
Cellular concrete	2.98	0.05	691	$27 \cdot 10^{-12}$
Plywood	6.10	0.023	299	$2.3 \cdot 10^{-12}$
Wood panels	9.27	0.015	538	$5.0 \cdot 10^{-12}$

TABLE 2
Range of Indoor Humidity Variation and Weight Change of the Sample Material

	Range of Daily Indoor Humidity Variations		Size and Range of Weight Change of the Sample Material		
	AH (g/kg)	RH (%)	Area (m^2)	Weight (kg)	Weight Change (g)
Case 0 (inert room)	3.5	25			
Case 1 (plasterboard)	2.3	15	0.450	4.3	5.0
Case 2 (chipboard)	3.0	19	0.537	8.8	7.0
Case 3 (cellular concrete)	2.2	15	0.125	4.3	6.0
Case 4 (plywood)	2.5	18	0.610	4.2	8.5
Case 5 (wood panels)	1.7	11	0.520	4.2	10.0

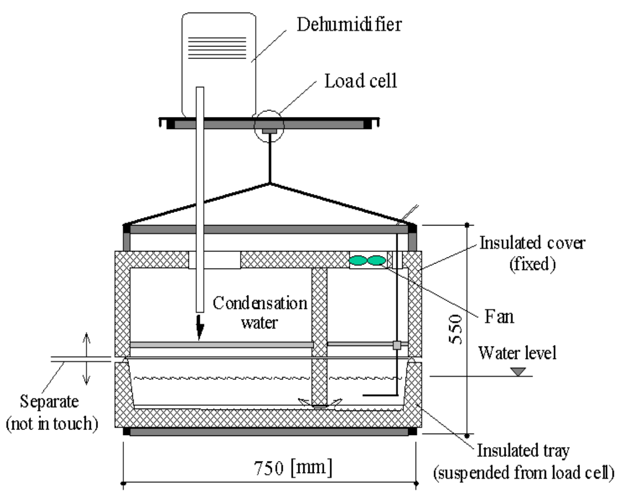

Figure 4 *Section of the evaporation/condensation device for humidity control in test cell.*

in indoor humidity when the set rate of humidity was delivered to or withdrawn from the air. These areas were determined by preliminary calculations with the new moisture model in the integrated simulation tool based on material properties from the literature. As the materials were exposed on both sides, the exposed surface areas were twice as large as the areas listed in the table.

In order to estimate the quantities of moisture absorbed and desorbed from the test materials, a sample of the material under test was weighed by suspending it from another load cell in the test cell during the experiment. This load cell also had a range and accuracy of 10 kg±3 g. The area of the "sample materials" varied from 0.12 m^2, to 0.61 m^2 and the weight from 2.9 kg to 8.8 kg.

Before testing, the materials were conditioned for a few weeks in another climate chamber where the indoor temperature and relative humidity were about 20°C and 60% RH—about the same conditions as during the subsequent experiments.

Experimental Conditions. Experimental conditions are listed in Table 2. First of all, the change of relative humidity was established in the empty chamber when vapor was added to and withdrawn from the air (Case 0). These excursions should be relatively large even with small rates of humidification/drying. Furthermore, since there were no vapor-absorbing materials in the test cell during the reference test, it should be possible to predict the humidity excursions theoretically with a simple model. This test would verify the inertness of the surface of the test cell and stress the importance of the very small rate of air change with outdoor air.

After the experiment, Case 0, the test cell was furnished with various test-building materials (Cases 1 to 5). Each test typically ran over just a few days each when daily cycles were studied. During the experiments, the indoor temperature was controlled to 20°C (±0.5°C), and the dehumidifier was set to increase the weight of the reservoir by 200 g in 12 hours. After the dehumidification, the heating element of the water reservoir was switched on to evaporate the water and decrease the weight of the reservoir by 200 g for the next 12 hours.

Measured Variation of Indoor Temperature and Humidity

Inert room (Case 0). The indoor absolute humidity varied between 6 g/kg and 9.5 g/kg, and the relative humidity varied between 40% RH and 65% RH.

According to a theoretical calculation of the moisture balance of the room when 200 g of water was delivered to and later withdrawn from the room in half-day cycles, the change of indoor absolute humidity during one day should be around 4.3 g/kg. But actually it was measured to be around 3.5 g/kg. For the whole room, this deviation amounts to about 36 g of moisture. The difference between the measurements and the theoretical expectation is an indication of the experimental error of using the test cell as an apparatus to test moisture absorption. The error can be attributed to the general errors of the experimental equipment used and is an indication that some limited moisture absorption actually did occur in the supposedly inert test cell. Such absorption may take place in paint on the inside of the steel walls and in the polyethylene foil on the inside of the southern facade.

Furnished room (Cases 1 to 5). The indoor temperature, weight of the water reservoir, humidity in the test cell, and weight of the sample material are shown in Figure 5 for the case with wood panels (Case 5). The indoor absolute humidity varied between 7.3 g/kg and 9.0 g/kg, and the relative humidity varied between 50% RH and 61% RH. Thus, the range of indoor humidity variation was about 1.7 g/kg—notably less than it would have been if the room had no furnishings (3.5 g/kg). Evidently, some of the moisture in the air was absorbed and desorbed by the wood panels.

The weight of the sample of wood panel (0.52 m^2) varied between 4208 g and 4220 g. The daily range of weight change was about 10.0 g, which amounts to 19.2 g/m^2. The total weight of the sample increased slightly during the experiment, so the test building materials did not quite reach a quasi-steady equilibrium moisture content during the four days of test.

The ranges of the indoor humidity variation and the weight change of the sample material in all cases are shown in Table 2. The range of the indoor humidity variation in the cases of furnished rooms (Cases 1 to 5) was in every case smaller than that of the inert room. It indicates that the indoor humidity variation was decreased by moisture absorption and desorption from the test materials. The range of absolute and relative indoor humidity variations of the room furnished with wood panels (AH: 1.7 g/kg; RH: 11%) was the smallest of all of the cases. The ranges of sample weight and relative humidity variations were estimated from Figure 5 (and similar figures for the cases not shown in detail in the paper).

Of the materials tested in the PASSYS cell, it seems that the wood panels had the best ability to absorb and desorb moisture from the room air. Another good moisture buffering material was cellular concrete, while plasterboard, chipboard, and plywood had somewhat smaller moisture buffering capacities.

Simulation of Indoor Humidity Conditions in the Experiment

The integrated simulation tool was used to simulate the indoor humidity in the tests. The program was run for the actual test conditions regarding moisture supply rates and surface areas of the materials, and now the needed sorption curves and vapor permeabilities had been measured in the laboratory for the actual materials.

The indoor absolute humidity of measurements and simulations with the integrated simulation tool are shown in Figure 6. Except for the room with chipboard, the model predictions are quite similar to the measured values. Especially in the case of cellular concrete and wood panels, the deviation between measurement and simulation of the absolute humidity is very small. However, for the room furnished with chipboard, there is a substantial deviation in the range from 1.0 g/kg to 1.5 g/kg between measurements and simulation. It may be suspected that the hygrothermal properties of the surface of this material are somewhat different from those of the interior parts of the material. Although the chipboard has the appearance of a homogeneous material, the surface of the chipboard is rather dense, while the interior of the material is more porous.

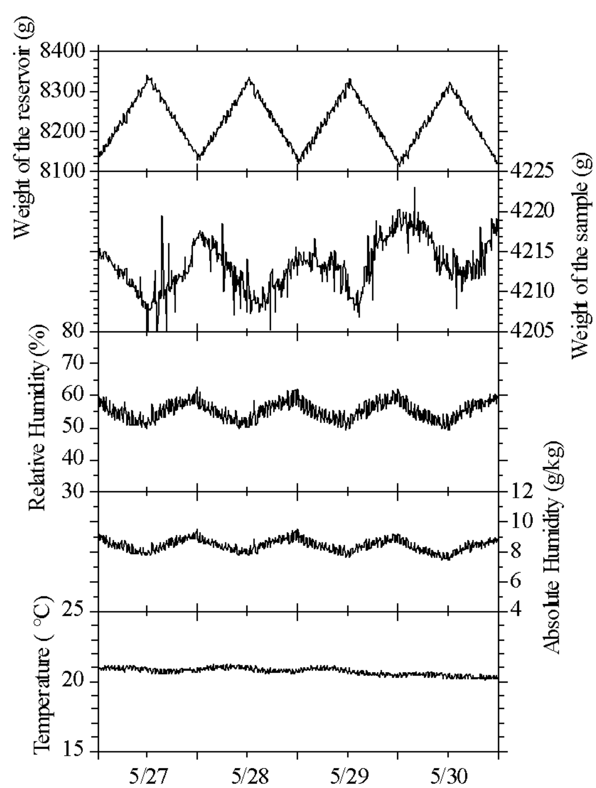

Figure 5 *Profiles developed over four days of indoor temperature and humidity in the test cell in Case 5 (wood panels).*

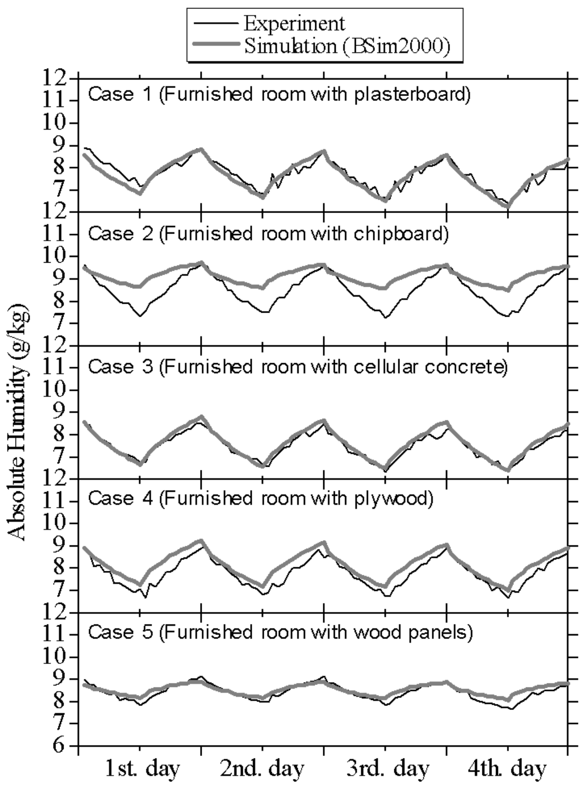

Figure 6 *Measured and predicted absolute humidity in the furnished room.*

PRACTICAL USE OF THE MODEL

The thermal part of the design tool, formerly known as *tsbi3*, is by itself a companion to other well-known building simulation tools such as DOE-2, EnergyPlus, and TRNSYS, and it has been used for more than a decade in Danish and international design practices and research institutions. It was also used in conjunction with IEA SHC Task 12. Building models can be made with, in principle, any number of zones; however, it is typical to use about 5 zones with about 25 building constructions. An annual simulation of such a building with the moisture model can be run in probably less than ten minutes on a normal personal computer depending on the chosen level of accuracy in the time and space discretization.

During autumn 2001, the moisture model in the integrated building simulation tool was tested on real building design projects by three major consulting engineering firms.

In one of the projects, a study of the relative humidity of the air in an office building was performed, taking into account the ability of the building materials to buffer the air humidity. The aim was to estimate the risk of condensation on a chilled ceiling and, in general, to estimate the indoor air quality. As a means to forecast this, the indoor relative humidity in a meeting room was predicted with the integrated building simulation tool both for the working days of a week in summer, as well as in winter. The building is mainly of concrete, but the floors have 10 mm wool carpet, there is a suspended ceiling with 20 mm mineral fiber boards, and the inner walls are clad with 13 mm painted plasterboard. The results are shown in Figures 7 and 8. According to research by Fang (1997) the relative humidity has an important influence on how occupants of buildings perceive the air quality, and a comfort diagram can be used to illustrate the effect for the actual case (see Figure 9). Dependent on the air temperature and relative humidity, the curves forecast the percentage of people that would be expected to express dissatisfaction with the indoor air quality.

Another project was an analysis of the moisture conditions of a planned archive for a museum. The most important parameter of the indoor climate for storing objects is the relative humidity. The moisture model was used to analyze the moisture conditions of the air in the rooms by changing the building materials and control of the heating systems.

The third project dealt with investigation of moisture problems in the exterior walls of an ice rink. This special form of indoor climate normally demands a certain configuration of layers in the exterior envelope to avoid moisture problems. The project has dealt with analyzing the problem after it has occurred and some different ways to resolve it.

The consulting firms' main conclusions after the testing are that the new moisture model will provide the possibility to

- study the relative humidity in rooms, taking into account the ability of building materials and furniture to absorb and desorb moisture,
- analyze the moisture level of constructions,
- analyze energy consumption in relation to construction moisture in building elements,
- analyze consequences of the indoor air quality by selecting different building materials,
- estimate risk of condensation,
- perform more realistic analysis, leading to reduced cost of the building.

SUMMARY AND CONCLUSION

An existing integrated simulation tool for dynamic thermal simulation of buildings has been extended with a transient model for moisture release and uptake in building materials. With the new model it is possible to make more accurate predictions of indoor humidity variations. Integrated in the model are calculations of the transient moisture conditions within all of the building's envelope constructions. Since the moisture conditions in building constructions depend very much on the indoor humidity, and since the building constructions also influence the indoor humidity, it is judged that the new development results in improved simulations of moisture conditions both for the indoor air and for the building constructions.

This paper has given a brief description of how the moisture model has been implemented in the existing thermal

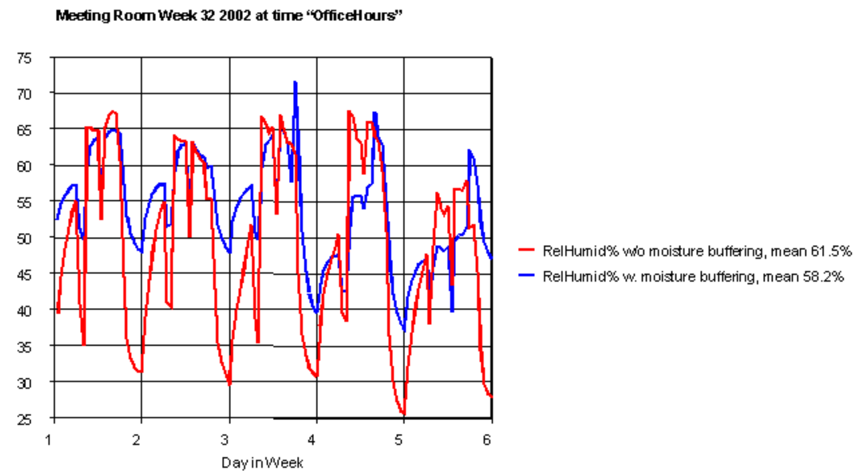

Figure 7 *Relative humidity in a meeting room during the working days of a week in winter. The results have been simulated with and without consideration of the moisture buffering effect of the building materials.*

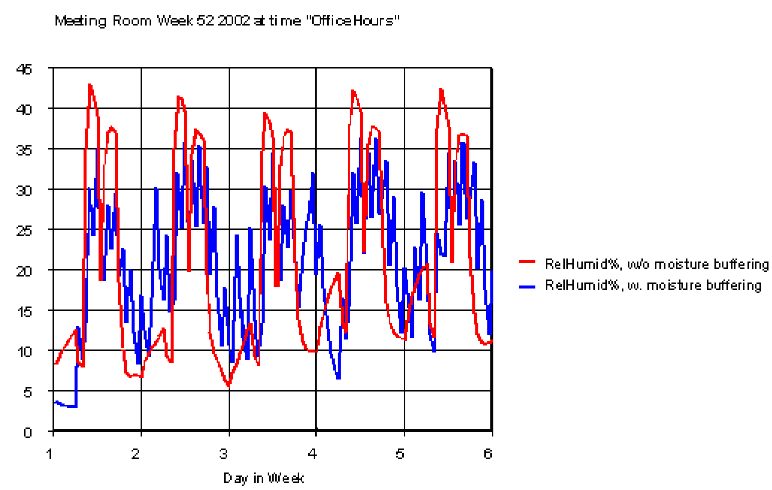

Figure 8 *Relative humidity in a meeting room during the working days of a week in winter. The results have been simulated with and without consideration of the moisture buffering effect of the building materials.*

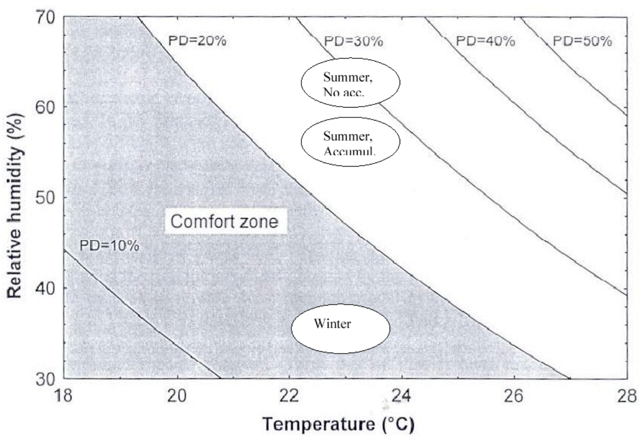

Figure 9 *Diagram illustrating the predicted percentage of occupants who are dissatisfied (PD) with the indoor hygrothermal conditions. Simulation results are shown for a summer and a winter week determined with or without consideration of humidity buffering when predicting the indoor humidity.*

building simulation tool, and some examples are shown of the practical use of the model as a design tool for consultants.

Validation of the new moisture model was begun with comparison against measurements in an outdoor test cell furnished with single materials. Almost quasi-steady, cyclic experiments were used to compare the indoor humidity variation and the numerical results of the integrated simulation tool with the new moisture model. Except for the case with chipboard as furnishing, the predictions of indoor humidity with the detailed model were in quite good agreement with the measured values.

ACKNOWLEDGMENTS

The work was carried out under the auspices of the Technical University of Denmark's International Center for Indoor Environment and Energy. The Center is funded by the Technical Research Council of Denmark. Additional support has been granted by the Danish Energy Agency under the Danish Ministry of Environment and Energy. The consulting engineering firms Carl Bro as, RAMBØLL, and Birch & Krogboe A/S performed the testing in practice. The support is gratefully acknowledged.

NOMENCLATURE

A = area, m^2
G = rate of moisture production in the indoor air, kg/s
g = vapor flux, kg/m^{2}s
i = index for space
j = index for time
n = air change by ventilation, s^{-1}
P = barometric pressure, Pa
p = partial pressure for water vapor, Pa
u = moisture content, kg/kg
V = volume, m^3
x = humidity ratio, kg/kg
Z = vapor diffusion resistance, m^{2}sPa/kg
β = convective moisture transfer coefficient, kg/(m^2 Pa s)
Δd = width of control volume, m
Δt = time step, s
δ = water vapor permeability, kg/(m s Pa)
ρ = density, kg/m^3

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