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# Model and Experiments for Hygrothermal Conditions of the Envelope and Indoor Air of Buildings

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## ABSTRACT

*This paper presents two linked research activities on hygrothermal conditions in buildings—the establishment of modeling capabilities for whole building analysis and experiments in a test cell of indoor hygrothermal variations.*

*A model for thermal simulation of buildings is given new capabilities for transient simulation of the indoor humidity by taking into account moisture buffering in building components and furnishing and the supply of humidity from indoor activities. The moisture conditions in all layers of the building envelope are calculated in the same simulation.*

*A test cell has been instrumented to measure indoor humidity conditions under transient exposure. The response in relative humidity of the air and the moisture content in adjacent building materials are measured when humidity is released into or removed from the room. The results are used to characterize the buffering capacity of different materials and to verify predictions of the numerical model.*

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## INTRODUCTION

Humidity in indoor spaces is one of the most important factors that determine the indoor air quality, and 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).

Ventilation with fresh air is a way to alleviate the problems of high indoor humidity, but ventilation requires energy to condition the air and to run the fans of the ventilation systems. Therefore, there is an interest in designing buildings for a suitable balance between moisture supply and required ventilation. However, it must always be considered that ventilation is important not only for reducing the indoor moisture levels but also for diluting other indoor air contaminants. The humidity condition of indoor air is the result of moisture supply from current activities and the actual ventilation rate. One must also consider how building materials and interior furnishings will buffer the variation in indoor humidity.

High indoor humidity is among the most important reasons for harmful accumulation of moisture in the building

envelope and can be a direct or indirect reason for extra energy consumption for thermal conditioning (heating or cooling) of the occupied spaces of buildings. This has been realized in the 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.

Furthermore, there seems to be an interest among building owners and some manufacturers of building materials, not least the organic sort, to promote the moisture buffering ability of these materials. This capacity of the materials is sometimes mentioned as an advantage for the perception of the indoor air quality and it is often referred to as a reason to consider the

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vapor barrier as superfluous in the exterior envelope (Ekofiber 2001).

Many approaches have been used by different researchers to model indoor humidity (e.g., Wang 2000). The approaches vary from simple steady-state models that completely disregard the indoor moisture buffering (Loudon 1971), over empirical models that acknowledge, but physically don't describe, the buffering effect (Tsuchiya 1980), to more physics-based models that consider the buffering in a surface layer of the building elements (e.g., the Effective Penetration Depth models by Kerestecioglu et al. [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 2000).

However, none of the above-mentioned models makes it possible to predict the hygrothermal conditions through the building envelope structure from inside to outside, and they do not always consider the temperature gradient that normally exists between the indoor climate and the exterior building envelope. But 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 the modular simulation environment IDA, which can be used as a component in a system where room moisture and temperature balances are 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 have some difficulty in 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 (Karagiozis and Salonvaara 1999 and Simonson and Salonvaara 2000a).

This paper describes a Danish modeling activity that was started in 1998 to extend an existing, transient building energy analysis tool with algorithms for calculation of the nonsteady indoor humidity condition and the moisture conditions in the adjacent building components and furniture. The idea was to take advantage of the already validated, detailed thermal model of the whole building. The model is based on a finite control volume method that is able to manage the nonlinear conditions.

As in all model development, it is important to validate. The previous European project PASSYS (European Commission 1994) was conducted around 1990 to develop a full-scale outdoor test facility that could be used to characterize passive solar energy components in different European climates and for empirical validation of thermal simulation programs. As will be described in this paper, the originally purely thermal measuring capability of these test cells can be extended to include also the room moisture conditions.

Previous measurements of whole building humidity conditions have been reported by Mitamura et al. (1999), Simonson and Salonvaara (2000b), and Plathner et al. (1999). The experimental activity described in this paper is meant to supplement such previous attempts. The measurement principle applied here is, however, somewhat different in that, to resemble the activity in an inhabited room, the experimental facility controls the delivery and extraction of humidity from the studied room and measures the response. Most other experimental facilities reported in literature work the other way around—they control the humidity and report what humidity exchanges are involved. The idea of the facility employed here comes from work by Padfield (1998).

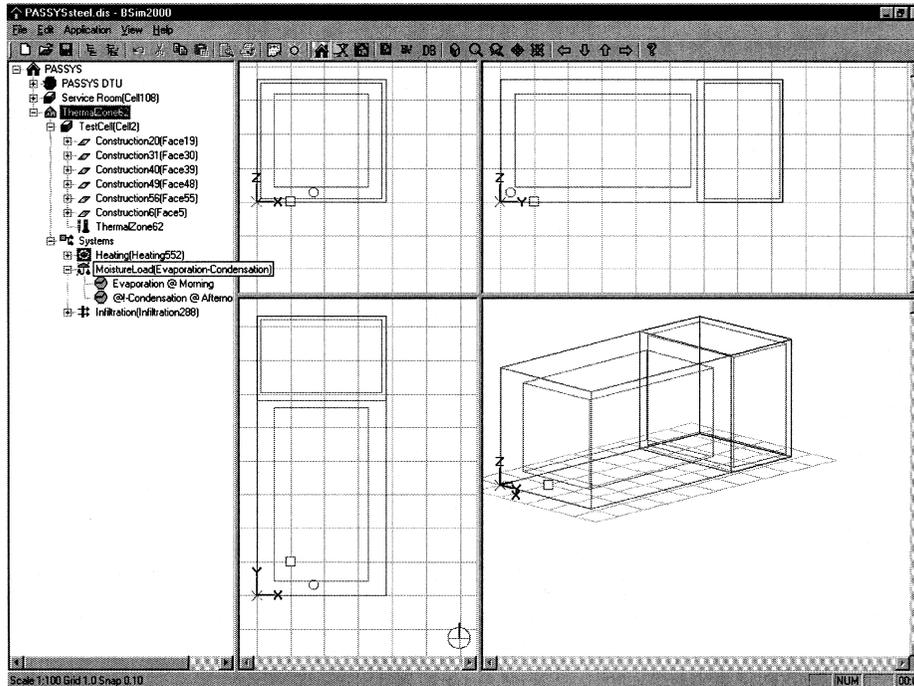
The objective of the work presented in this paper can now be summarized as to develop and carefully validate a computer tool to carry out parametric simulations in combination with measurements of whole building moisture conditions.

Finally, the authors would like to acknowledge the intense interest seen these years among researchers to model and measure the integral moisture conditions of buildings and components. In connection with the Healthy Buildings Conference in 2000, a workshop was organized to express consensus on research and development work into building materials that moderate the indoor humidity (Virtanen et al. 2000). The workshop summary also includes a summary of related literature.

## **MODELING MOISTURE CONDITIONS OF INDOOR AIR AND BUILDING CONSTRUCTIONS**

One cannot predict moisture conditions without knowing the thermal conditions. It is natural, therefore, to develop a model for prediction of whole building moisture conditions as an extension of an existing tool for a detailed thermal analysis of buildings. Such a tool will already predict the thermal condition of the indoor environment and all the adjacent building components. Normally, the thermal calculation tools are rather elaborate themselves, their thermal predictions have been verified already, and they come with an already existing user interface. One such program is BSim (a reference used in this paper to indicate the topic of the program: Building Simulation).

BSim is a flexible computer program for analysis of indoor climate, energy consumption, solar distribution and shading conditions, and daylight performance of buildings (Wittchen et al. 2000) (see Figure 1). The core of the system is a building data model shared by the design tools and a common database with typical building materials, constructions, windows, and doors. BSim was released in May 2000 and is being used by consulting engineering companies, engineering schools, research institutes, and others who have a need to simulate the thermal indoor climate, daylight performance, energy consumption, control factors, energy conserving design of buildings, and utilization of passive solar energy.



**Figure 1** Graphical interface of the BSim program showing the model of the test cell from which experimental data will be used for comparison with the model predictions.

In BSim, a model editor and visualization tool, a tool for analysis of solar distribution and shadows in and around buildings, and a tool for thermal simulations, which is an extended and improved version of tsbi3, are integrated (Johnsen and Grau 1994). The thermal simulation tool is based on the finite control volume method. It has been widely validated and has been employed in several international research projects (e.g., EU COMBINE [Augenbroe 1995] and IEA Task 12 [Lomas et al. 1994]). From within BSim it is possible to link to a few external programs, e.g., a program allowing the user to create a building model by using CAD drawing (DXF format) as the basis (Grau and Wittchen 1999).

### Extension of BSim with Moisture Calculations

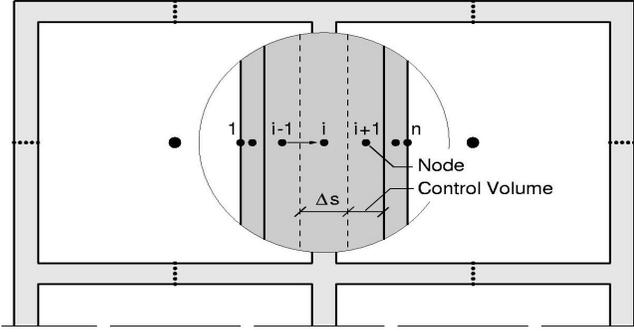
A building is understood by BSim as a number of zones, separated from each other and from outside air, or from possible virtual zones, by constructions of different kinds. A humidity balance equation is set up separately for each zone. The balance equation includes moisture exchange by infiltration, ventilation and “mixing” with the surroundings (the outdoor climate and the adjacent zones), humidity exchanged by convective transfer to and from constructions and furnishing, and moisture released to the zones as a result of various activities. A dynamic calculation of moisture conditions is carried out for every single construction and furnishing. The zones on each side of the construction give the boundary conditions.

Constructions (and furnishings) are considered as composite building components consisting of several layers and materials. Every single material layer is again subdivided into control volumes for which the calculations are carried out. A node point in the center of each control volume represents the conditions in the whole volume.

In each time step, calculations of the temperature conditions in the control volumes of the constructions and in the zones have to be carried out before calculating the moisture conditions. The same control volumes are used for the thermal and for the moisture calculations. Details about the underlying theoretical methodology are given in the following subsections.

**Discretized Model of a Building.** A building may consist of an arbitrary number of zones and an arbitrary number of 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  $T$  ( $^{\circ}\text{C}$ ) and the humidity ratio of the air  $x$  (kg/kg). The air in a zone is considered as being fully mixed.

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. Thick layers are subdivided into 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. Furnishing is considered as build-



**Figure 2** Part of a plan of a building as understood by BSim 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.

ing constructions that face the same zone on both sides or that are calculated from one side and to an adiabatic, vapor-tight center.

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

### Humidity Balance for the Zone Air

The following influences on the humidity condition of 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, etc.)
- Penetration of humidity from outdoor air by infiltration and venting
- Supply of humid air from ventilation systems
- Humid air transferred from other zones

Humidity balances for zones are made up for the humidity ratio  $x$  (kg/kg) (mass of water vapor per mass of dry air). The time dependency of changing the moisture content of air is taken into account. When the different contributions of humidity to the air are summed up as  $\Sigma G$ , the equation for moisture balance over a time step  $\Delta t$  reads

$$V \cdot \rho_{air} \frac{x^{new} - x^{old}}{\Delta t} = \Sigma G. \quad (1)$$

where

- $V$  = volume of the zone,  $m^3$ ;
- $\rho$  = density of the air,  $kg/m^3$ .

The humidity transfer between the construction surfaces and the zone air is governed by the convective moisture transfer coefficients and is calculated from

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

where

- $G_{constr}$  = rate of induced humidity to the air from all surfaces,  $kg/s$ ;
- $A_{surf}$  = area of a surface,  $m^2$ ;
- $\beta$  = convective moisture transfer coefficient,  $kg/(m^2 \cdot s \cdot Pa)$ ;
- $p$  = partial pressure for water vapor (“vapor pressure”),  $Pa$ .

In BSim, depending on a parameter chosen by the user, the interior heat transfer coefficient, as well as the moisture transfer coefficient, can either be constants or can be derived from equations for natural surface convection from the *ASHRAE Handbook—Fundamentals* and the Lewis relation (see Rode 2000). In case constant coefficients are used, the default value for  $\beta$ ,  $2.0 \cdot 10^{-8} \text{ kg}/(m^2 \cdot s \cdot Pa)$ , is used for indoor surfaces.

The following equations can be derived from the universal gas law for the relation between the vapor pressure and the humidity ratio of the air:

$$x = 0.622 \frac{p}{P - p} \quad (3)$$

$$p = \frac{x}{x + 0.622} P$$

where

- $P$  = the barometric pressure,  $Pa$  (101325  $Pa$  at sea level).

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

$$G_{vent} = \sum_{air\ sources} n_{vent} V \rho (x_{vent} - x_{air}) \quad (4)$$

where

- $G_{vent}$  = humidity supplied by the ventilation air,  $kg/s$ ;
- $n_{vent}$  = air change in the zone associated with each of the air sources,  $s^{-1}$ ;
- $x_{vent}$  = humidity ratio of the air as it enters the zone,  $kg/kg$ .

Moisture contribution from “systems” may originate from people or from other moisture loads in the zone. The influences of these systems on the humidity of the air may vary according to defined schedules or various control strategies. The humidity contributions from these sources will be collected in one single quantity called  $G_{sysr}$ .

Now, the total humidity balance 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 sign and known, or *old*, conditions on the other, the following results:

$$x_{air}^{new} \left( 1 + \frac{\Delta t}{V \rho_{air}^{constr}} \sum A_{surf} \beta \frac{P}{x_{air}^{old} + 0.622} + \Delta t \sum_{air\ sources} n_{vent} \right) = x_{air}^{old} + \frac{\Delta t}{V \rho_{air}^{constr}} \sum A_{surf} \beta p_{surf} + \Delta t \sum_{air\ sources} n_{vent} x_{vent} + \frac{\Delta t}{V \rho_{air}} G_{syst} \quad (5)$$

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

### Moisture Transport in the Constructions

The model for moisture transport in the constructions considers moisture transport in the form of vapor diffusion. The moisture transport internally in the constructions is described in a transient way by considering the moisture buffering capacity of each layer. An example of the breakdown of a construction into node points and control volumes is shown in Figure 2. The control volumes are indicated by the letter *i*.

A calculation is carried out for each control volume and time step of how much moisture is induced by vapor diffusion and how much is removed. The sum of these contributions gives rise to a change of moisture content from one time step to the next. Using the sorption curves of the material, the new moisture content can be recalculated into new relative humidity and vapor pressure. The first implementation of the model does not consider hysteresis in the sorption curves since only the absorption curve is used, but it is planned for later developments to take into account the difference between the curves for absorption and desorption according to the empirical model described by Pedersen (1990).

Consider the control volume *i* in the wall of Figure 2. Vapor diffusion from the adjacent control volume *i-1* can be calculated on the basis of Fick's law. It is assumed that the two materials each have their individual water vapor permeability and that the control volumes each have their individual thickness. The vapor permeability is taken as a function of equilibrium relative humidity of the materials. The vapor flux over the interface between the two control volumes in the time step from time index *j* to *j + 1* is calculated as

$$g_i^{j+1} = \frac{p_i^{j+1} - p_{i-1}^{j+1}}{\frac{\Delta s_{i-1}}{2\delta_{i-1}} + \frac{\Delta s_i}{2\delta_i} + Z_i} \quad (6)$$

where

- $g$  = vapor flux, kg/m<sup>2</sup>s;
- $\Delta s$  = thickness of the control volume, m;
- $\delta$  = water vapor permeability of the material, kg/(m s Pa);
- $Z$  = a possible vapor diffusion resistance *between* control volumes, Pa m<sup>2</sup> s /kg;
- $i$  = index for the place;

$j$  = index for the time.

The sum of vapor diffusion resistances between nodes *i-1* and *i* is expressed in the denominator. The vapor diffusion resistance,  $Z_i$ , between the control volumes will be zero unless another value is specified for the interface between two layers (e.g., caused by a vapor retarder or a layer of paint). The vapor permeability,  $\delta$ , is determined for each control volume as a function of local moisture content.

On the basis of Equation 6 the vapor flux is calculated from the vapor pressures at the end of the time step. When the calculation has arrived at time step *j*, and the conditions are to be calculated up to time *j+1*, the condition at the end of this time step is not yet known. An implicit calculation procedure is used to calculate the new condition as described below.

Throughout the time step, the implicitly indicated vapor flux from Equation 6 is assumed to be constant, and the increase in moisture content for the control volume *i* can be expressed by the following moisture balance:

$$\rho_i \Delta s_i \frac{u_i^{j+1} - u_i^j}{\Delta t} = -(g_{i+1}^{j+1} - g_i^{j+1}) \quad (7)$$

where

- $u$  = moisture content (mass of moisture per mass of dry material), kg/kg;
- $\Delta t$  = size of the time step, s.

By expressing the change in moisture content as a change in the relative humidity multiplied by the specific moisture capacity and by inserting the terms for the vapor fluxes  $g$  from Equation 6, the following equation can be set up:

$$(\rho \xi)_i \Delta s_i \frac{\varphi_i^{j+1} - \varphi_i^j}{\Delta t} = \frac{p_{i-1}^{j+1} - p_i^{j+1}}{\frac{\Delta s_{i-1}}{2\delta_{i-1}} + \frac{\Delta s_i}{2\delta_i} + Z_i} + \frac{p_{i+1}^{j+1} - p_i^{j+1}}{\frac{\Delta s_i}{2\delta_i} + \frac{\Delta s_{i+1}}{2\delta_{i+1}} + Z_{i+1}} \quad (8)$$

where

- $\xi$  = specific moisture capacity (slope of the sorption curve), kg/kg;
- $\varphi$  = the relative humidity.

The calculation procedure now follows a sequence of steps 1 through 3:

1. The relative humidity is the ratio between vapor pressure,  $p$ , and saturation vapor pressure,  $p_s$ , at the same time and location. The saturation vapor pressure depends only on the temperature and can therefore be calculated for all control volumes every time the temperature has been determined. Equation 8 can now be written in vapor pressures alone

$$\begin{aligned}
(\rho\xi)_i \Delta s_i \frac{p_i^{j+1} - p_i^j}{\Delta t} &= \frac{p_{i-1}^{j+1} - p_i^{j+1}}{\frac{\Delta s_{i-1}}{2\delta_{i-1}} + \frac{\Delta s_i}{2\delta_i} + Z_i} \\
&+ \frac{p_{i+1}^{j+1} - p_i^{j+1}}{\frac{\Delta s_i}{2\delta_i} + \frac{\Delta s_{i+1}}{2\delta_{i+1}} + Z_{i+1}}.
\end{aligned} \quad (9)$$

The boundary node  $i=1$  is at face 1 of the construction and is calculated without thickness ( $\Delta s_i=0$ ). The following equation expresses the vapor flow balance over this node:

$$0 = \beta_{surface}(p_{air} - p_1^{j+1}) + \frac{p_2^{j+1} - p_1^{j+1}}{\frac{\Delta s_2}{2\delta_2} + Z_2}. \quad (10)$$

An equation corresponding to Equation 10 also exists for surface 2 ( $i=n$ ), and the whole equation system is solved simultaneously for all control volumes. Since the surface control volumes have no thickness and, thus, no moisture capacity, the model considers surface condensation as an accumulation in the first control volume behind the surface. For this reason and in general to achieve good accuracy in the simulation of the humidity exchange between materials and indoor air, it is essential to use thin control volumes near the surfaces (e.g., some fraction of the effective penetration depth of the material for diurnal moisture variation).

2. Now the “new” vapor pressure distribution has been determined. However, since the whole problem is nonlinear because the moisture capacity is not a constant value, a special procedure is followed to ensure that the mass balance will be correct. The vapor pressures just found are regarded as preliminary predictions of the new values. By employing Equations 6 and 7, the new moisture contents are found in each control volume. Since these equations express the moisture balance of each control volume, it can be ensured that the entire moisture balance of each construction is maintained.
3. Finally, the equilibrium relative humidity is determined for each control volume by taking the calculated moisture contents and using the sorption curve for the relevant material.

## VALIDATION OF THE MODEL

### Experimental Validation of the Model Against Test Cell Data

**Experimental Setting.** During the years 1986 to 1993, an extensive research project PASSYS was carried out under the auspices of the European Commission’s DG XII to investigate passive solar energy techniques and to validate a program for thermal simulation of buildings (European Commission

1994). As part of this project, outdoor test facilities were established at 14 different sites in 11 European countries.

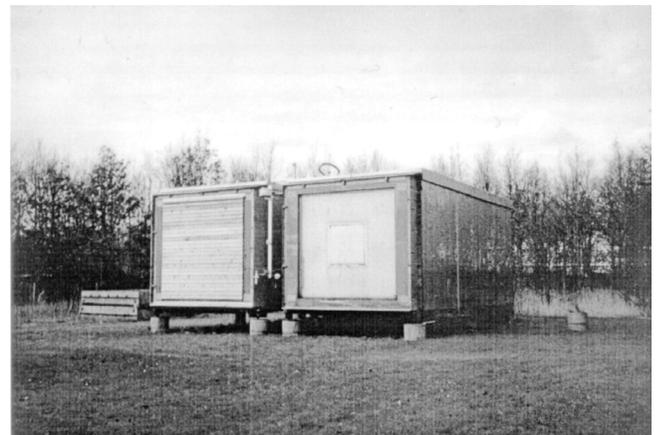
The facilities consist of highly insulated steel boxes with an indoor floor area of 13.8 m<sup>2</sup> (149 ft<sup>2</sup>), and a room height of 2.75 m (9.0 ft), so the volume is 38.0 m<sup>3</sup> (1340 ft<sup>3</sup>). Two such cells are located at the Technical University of Denmark. The walls, roofs, and floors of the cells consist of steel, both on the inside and on the outside, and they are insulated with up to 50 cm (20 in.) of polystyrene and mineral wool. The cells stand on pillars so they are not in touch with the ground. The wall on the southern facade is exchangeable, as the intention was to test various passive solar heating components. A picture of the test cells is shown in Figure 3 and an isometric view of one of them is shown in Figure 4.

The cells are very airtight with measured air change rates of about 0.20 h<sup>-1</sup> at 50 Pa (0.015 in. Hg) pressure difference. The air change rate measured with tracer gas using the decay method without pressurization was about 0.01 h<sup>-1</sup>.

In the northern end of the test cells are 8.6 m<sup>2</sup> (93 ft<sup>2</sup>) service rooms with the cooling and control systems. Within the test room of each cell is an air distribution system (with conduits entirely within the cell) connected to heating and cooling coils. The cells are instrumented with sensors for measuring both the outdoor climate (three components of solar radiation, ambient temperature, relative humidity, and external surface temperatures) and the indoor conditions (air temperatures, surface temperatures, heating, cooling and fan powers, heat fluxes, air infiltration rate, and air velocity). Furthermore, the indoor relative humidity is measured with capacitive moisture sensors. The data acquisition system is located in a neighboring building from where the operation of the systems of the test cells can also be controlled.

A well-insulated wall with a vapor-tight polyethylene sheet on the inner surface has been installed as the exchangeable southern facade.

**Experimental Plan.** One of the test cells has been used as a full-scale test chamber to study the moisture buffering effect of spaces and building envelope components. For this



**Figure 3** Photo of the two PASSYS test cells.

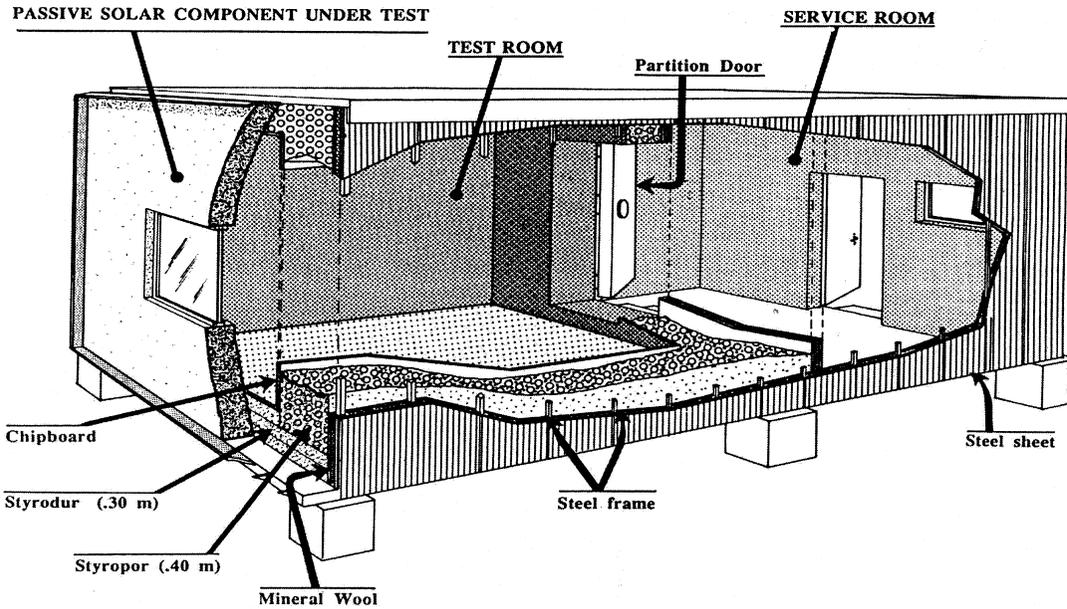


Figure 4 Isometric view of a PASSYS cell.

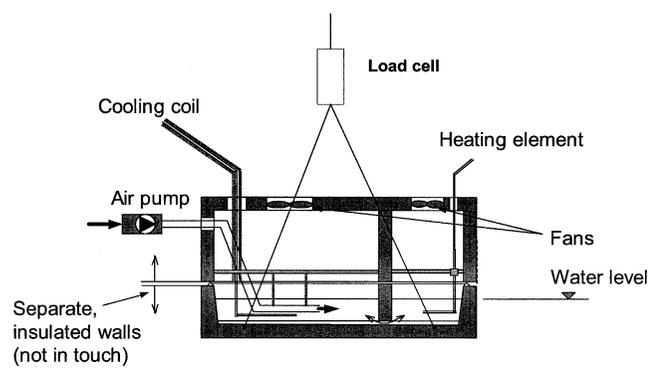


Figure 5 Section of the condensation/evaporation unit for humidity conditioning of the PASSYS cell.

purpose, new equipment for humidifying and desiccating the cell has been installed. The setup for the equipment is inspired by methods developed by Padfield (1998) for a small (0.5 m<sup>3</sup>, 18 ft<sup>3</sup>) test chamber in the laboratory.

In the experiment, humidification takes place by evaporation of moisture from a reservoir of water that is heated by an electric heating element. Likewise, extraction of humidity from the air takes place by blowing the air over a tray of chilled water. The reservoir of condensed water is in contact with the reservoir for (re-) evaporation, so the water circulates within one system only. The tray with the reservoirs is weighed with a load cell, and the control system of the PASSYS cell makes it possible to control the rates of condensation and evaporation according to a predefined schedule. A schematic diagram of the apparatus is shown in Figure 5. Using the apparatus, it is possible by the evaporation of water to imitate the vapor production in an inhabited room. By condensation, it is possi-

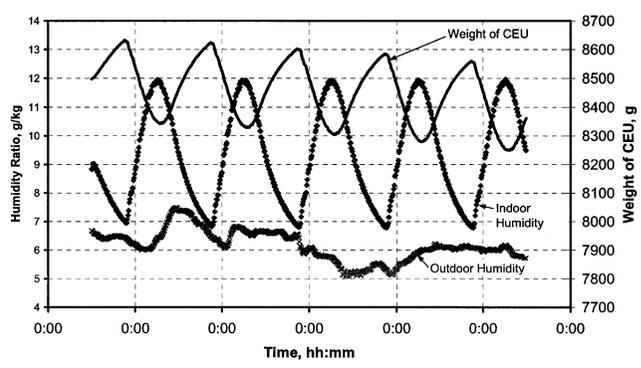


Figure 6 Humidity ratio outdoors and in the PASSYS cell, and weight of the condensation/evaporation unit (CEU), during a five-day preliminary test period of the empty cell.

ble to imitate, in a controlled way, the extraction of water from a room as it would normally take place by ventilation. The objective of the experiment is to measure the response of the room in terms of relative humidity (or water vapor content) and to use these results for comparison with predictions with BSim.

A preliminary test of the PASSYS cell with the condensation/evaporation unit was conducted over a five-day period when the average indoor humidity ratio was 9.3 g/kg, and the outdoor average humidity ratio was 6.2 g/kg. The indoor humidity ratio varied daily by approximately  $\pm 2.5$  g/kg around a rather constant average value when the control of the condensation/evaporation unit was set so its weight decreased by about 21 g/day (0.046 lb/day) (see Figure 6). From these data, the air change rate can be estimated as

$$n = \frac{\dot{m}}{V\rho(x_{in} - x_{out})}$$

$$= \frac{(21\text{g})/(\text{day})}{38\text{m}^3 \cdot 1.2\text{kg}/\text{m}^3 \cdot (9.3 - 6.2\text{g}/\text{kg}) \cdot 24\text{h}/(\text{day})} = 0.006\text{h}^{-1} \quad (11)$$

where

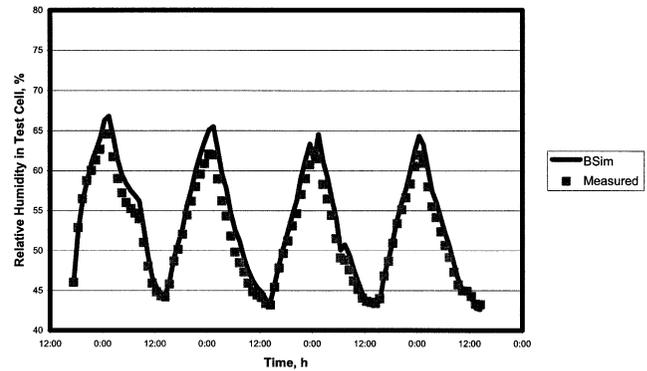
$\dot{m}$  = rate of moisture removal from the test cell, g/h.

This corresponds well with the results of the air change measurements using tracer gas. In subsequent tests, the control of the condensation/evaporation unit was set with a small gradual decrease of its weight of water, so as to compensate for the test cell's loss of humidity due to infiltration.

The measurement plan evolves over several steps, where the second step is ongoing by the time of writing this paper.

- *Step 1, the inert room (isothermal):* Some reference tests have been carried out to test the performance of the humidity control system and to measure the changes of relative humidity in the empty chamber when vapor is added to and extracted from the air. The anticipation is that these excursions should be relatively large even for small rates of humidification/drying. Since there are no vapor-absorbing materials, the humidity excursions should be rather straightforward to predict theoretically, and hence, these tests will verify the inertness of the surfaces of the test cell. The tests typically run over just a few days each when daily cycles are being studied.
- *Step 2, the furnished room (isothermal).* During the experiments that take place in the second step, the cell is furnished with typical building materials—from almost nonhygroscopic materials, such as gypsum and mineral wool, over more hygroscopic silicate materials, such as aerated concrete, to organic and hygroscopic materials such as wood. Initially, only single materials have been tested, but later, multi-layered composite structures will also be set up. For instance, the plan is to study the effect of different vapor retarder systems in the structures, as well as the effect of various surface coatings. Furthermore, it will be possible to test other materials that are present in an indoor climate (e.g., textiles and other material for furniture, curtains, and paper [books]). In this paper, some results of humidity variations in the test cell furnished with a board of plywood of about 3 m<sup>2</sup> (32 ft<sup>2</sup>) will be illustrated. The materials are mounted in racks of steel so they are exposed on both sides. The duration of each experiment is on the order of about one week.
- *Further steps:* Eventually, the cell will be used for nonisothermal testing, where the indoor temperature will vary diurnally in a natural pattern.

In addition to the experimental results shown in this paper, more recent results are reported by Mitamura et al. (2001).



**Figure 7** Measured and predicted relative humidity in the empty test cell when moisture is added and withdrawn in daily cycles.

**Modeling of the Experimental Results.** The following two test cell results are shown for comparison with BSim predictions:

1. Humidity variations in the empty chamber during a four-day period when humidity is added to and withdrawn from the air in daily cycles. The cycles consisted of interchanging periods, each 12 hours long, with constant humidification or drying of the air in the test cell by rates of 0.016 kg/h (0.035 lb/h). The removal of humidity in this way is meant to represent, in a controlled way, the dilution of indoor humidity by ventilation, whereas the periodic addition of humidity is meant to represent moisture release during occupation of a room. In this analogy, one could assume the removal by ventilation to be active always, so that the real moisture contribution corresponds to 0.032 kg/h (0.070 lbs/hr), matching the evaporation from one adult person doing office work in the room for about 75% of the time.
2. The humidity variation for a similar period, and under similar conditions of humidification and drying, when the room is furnished with a plywood board of dimensions 2430 × 1220 × 16 mm (95.7 × 48.0 × 5/8 in). The plywood board was put in an upright position in the middle of the test cell. The air-conditioning system of the test cell and an extra fan on the floor caused a high level of air circulation around the surface of the specimens with air velocities of roughly 0.3 ± 0.2 m/s (1 ± 0.6 ft/s). Before being brought to the test cell, the plywood had been adjusted for a month to a constant climate of 44% RH.

The results of measurements and simulations with BSim are shown for the empty test cell in Figure 7. The simulation uses the measured evaporation and condensation rates as input. In addition, the simulation is set up with a heating system that keeps the same constant temperature of 20°C (68°F) as was measured in the room. Also, the simulation considers the small infiltration rate that has been measured for the box to take into account the associated small dilution of the vapor concentration. Both this experiment, and the other with

plywood, were undertaken in a winter period when the outdoor temperature was around 0°C (32°F).

Similar results for the test cell furnished with the plywood board are shown in Figure 8. This experiment was conducted separately from the previous one for the empty chamber, so the moisture evaporation and condensation rates turned out to be slightly different. Figure 8 includes results of simulations of the relative humidity under the actual test conditions both with and without considering the presence of the plywood in the room.

**Discussion of the Modeling Result.** As should be anticipated, the model predicts quite well the relative humidity of the air in the test cell when the cell is empty and all surfaces are impervious (see Figure 7). The maximum deviation between measurement and calculation is around 4% RH (1.4% deviation on average). This is the same magnitude as the accuracy of the RH sensors (2%). Hence, it may be assumed that the walls and instruments in the otherwise empty test cell are rather nonabsorbing. The effect of diluting the room’s vapor concentration by the small infiltration rate seems to be well taken into account by the model.

In the case with plywood in the test cell, it appears to show some more deviation between calculation and measurement because some of the highest measured RH peaks are not met by the calculation. However, the maximum deviation, 4.5% RH, is only slightly higher than it was for the empty cell, and the average deviation is 1.3%. The amplitude between high and low relative humidity was measured to be 8.8% RH on average for the four-day period, while it was 7.2% in the calculations.

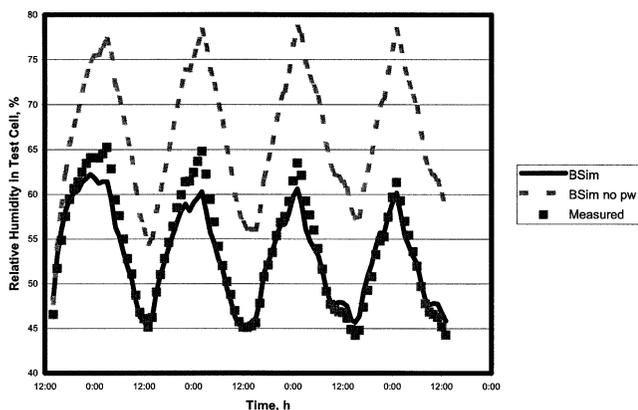
The calculations used property data for plywood from a database, and that could be the reason for some deviation. Vapor permeability (from dry and wet cup measurements) and sorption curves (both for absorption and desorption) are later being measured for the materials used in the test cell. Also, it should be borne in mind that many wood-based materials do

not absorb moisture entirely according to established physical laws for porous materials (so called “non-Fickian” behavior; Håkansson 1998), and therefore may be difficult to model.

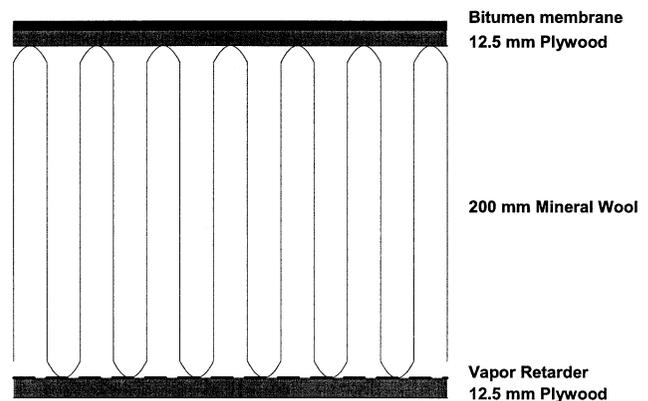
The calculation for the same test conditions as in the test with plywood, but without plywood in the room (the dashed curve in Figure 8), show some higher levels for the relative humidity and also a higher amplitude (10.7% RH). The reason for the higher RH level in this figure compared to Figure 6 is that the moisture release happened to be a little higher in this experiment than it was in the experiment with the empty test cell. When there was plywood in the cell, it may have absorbed this extra moisture from the air since the plywood was equilibrated prior to the test in a slightly drier environment. The comparison between the two calculation results in Figure 8 shows that there is some moisture buffering effect on the test cell climate of the presence of the plywood, as indicated by the difference in calculated RH amplitudes.

### Prediction of Moisture Conditions Within Building Structures

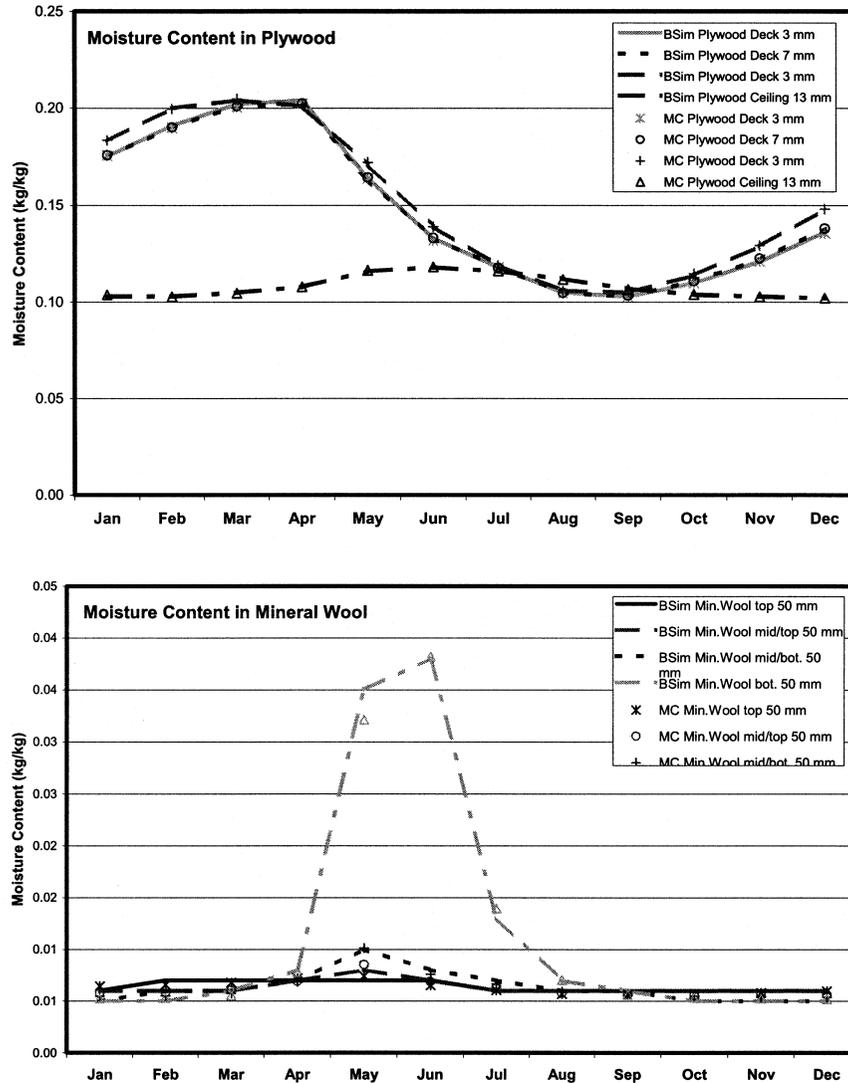
An anticipated advantage of the simultaneous calculation of the moisture conditions of the indoor environment and the surrounding building structure is that better predictions of the moisture conditions of both can be made when their interrelation is considered. It is important, therefore, to also verify the calculation of moisture conditions within the envelope. For this purpose, a calculation was set up in BSim of the moisture conditions in a roof structure for a predefined indoor climatic condition. A simulation was made for a room with a powerful air-conditioning system that would always maintain 20°C and 50% RH in the indoor climate of the calculation. The roof structure that was simulated is shown in Figure 9. The roof was a horizontal stressed skin roof with 13 mm (0.5 in.) plywood decks both on top of and below the 200 mm (8 in.) of mineral wool insulation. The roof was simulated with a black bitumen roof membrane on the outside, and it was exposed to an outdoor climate taken from the Design Reference Year for



**Figure 8** Measured and predicted relative humidity in the test cell furnished with a plywood board when moisture is added and withdrawn in daily cycles.



**Figure 9** Roof structure for which the moisture conditions are simulated in the BSim and MC programs.



**Figure 10** Comparison between BSim (lines) and MC (symbols) predictions of moisture content in the plywood boards and in the insulation layers of the roof structure.

Copenhagen—an hourly weather data file (Jensen and Lund 1995). The roof had a vapor retarder with a fairly low vapor diffusion resistance of 10 GPa·m<sup>2</sup>·s/kg (vapor permeability 1.7 perm).

For comparison, the same roof was simulated with the MC program (Pedersen 1990). MC (a reference used in this paper to indicate the topic of the program, moisture in constructions) is a tool for hourly simulation of combined heat and moisture transport in individual building constructions that are exposed to prescribed indoor and outdoor climates. The program has been validated previously (Rode and Burch 1995; IEA 1996b). The BSim and MC programs are not compatible in the way they treat the outdoor boundary conditions. Both programs calculate the solar irradiation hour by hour. But while the MC program makes a prediction of the

longwave radiation to the sky and a convective heat loss to the outdoor air that depends on the wind speed, BSim makes a simpler calculation of the heat loss to the ambient described by a constant heat transfer coefficient. Changes were made to the MC model to ensure that the predictions of the thermal roof surface conditions would be similar.

A one-year calculation of the humidity conditions in the layers within the roof structure was made with both programs starting from similar initial conditions. The calculation results for different layers of the roof are shown in Figure 10.

The results correspond very well with deviations of moisture contents of less than 1% for the plywood and less than 9% for the insulation. The results are not surprising since much of the experience from the development of the MC program is carried over in the moisture model for BSim. The good

comparison shown here is mainly an indication that the operation has been successful. But also, since overall moisture balances are checked in the MC program, it can be inferred that the moisture balance is conserved in BSim as postulated previously in the description of step 2 of the calculation procedure.

## SUMMARY AND CONCLUSION

A model to simulate the transient moisture response of rooms has been developed as an extension to an existing thermal simulation tool for buildings. With the extended tool it is possible to simultaneously predict in the same calculations

- the development of humidity of indoor spaces of buildings in response to adjacent building constructions and materials that buffer the moisture and
- the moisture conditions in the full depth of the building structures, from inside to outside.

The advantage of this modeling methodology is that, compared to previous attempts to model either the indoor humidity conditions or the conditions in the building envelope,

- the new methodology considers not only the surface layers of the materials that are adjacent to the indoor air as moisture buffers and
- for prediction of humidity conditions in exterior envelopes, the humidity condition of the indoor environment is a very important boundary condition, for which model users previously had to make assumptions. With the proposed model, the internal boundary condition for constructions is part of the simulation. The inside boundary condition will be determined by the geometry, use, and air conditioning (heating, cooling and ventilation) of the indoor space.

The model predictions of moisture conditions within an exterior building envelope component have been validated against predictions with a well-established model to simulate hygrothermal conditions in building structures. The comparison was good.

The model predictions of humidity conditions in the air of an indoor climate are validated empirically against full-scale measurements from an outdoor test facility—a well-insulated, vapor- and airtight test chamber with constant indoor temperature and with a possibility to release moisture to the indoor test cell air, or to remove moisture from it, at well defined rates. Comparison was made against experimental results where the test cell had either been empty with all interior surfaces impervious to vapor transport or to another case where a plywood board was located in the room as a furnishing with some moisture buffering capacity. In both cases, it was possible to make satisfactory predictions of the indoor humidity conditions. The measurements with moisture buffering materials will be continued to cover a wider range of typical

selections of furnishings and building materials in the indoor climate.

There is a great need for further experiments of hygrothermal conditions for whole buildings that will demonstrate in full scale the interaction between indoor spaces, building envelope components, and furnishings. Such experiments will serve both to characterize the moisture buffering capability of building materials and to provide experimental data sets for verification of models like the one presented in this paper.

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