

# SYNCHRONOUS CALCULATION OF TRANSIENT HYGROTHERMAL CONDITIONS OF INDOOR SPACES AND BUILDING ENVELOPES

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## ABSTRACT

An existing computer model for dynamic thermal analysis of buildings has been extended to consider the moisture balance of the interior spaces. The new model takes into consideration not only the production of humidity in the spaces and their ventilation with outdoor or conditioned air, but also the buffering of moisture in interior and exterior building constructions, and in interior furnishing. The model is included in an existing integrated building design tool, *BSim2000*. The perspective of the integrated model is to predict in a simultaneous calculation both the humidity conditions of indoor spaces, and the thermal and moisture conditions through the whole thickness of adjacent building constructions. Since the hygrothermal conditions of envelopes, furnishing and indoor spaces influence on each other, better prediction capabilities should be achieved in all.

## INTRODUCTION

Humidity in indoor spaces is one of the most important factors to determine the indoor air quality, and many health related problems in the indoor environment can be associated with high indoor humidity. Furthermore, high indoor humidity is among the most important reasons for harmful accumulation of moisture in the building envelope, and can be a reason for extra energy consumption for heating or cooling of the occupied spaces of buildings.

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 an interest to be able to design buildings for a suitable balance between moisture supply and required ventilation. However, the humidity condition of indoor air is result not only of moisture supply from current activities and the actual ventilation rate. It must be considered also that many building materials and interior furnishing are hygroscopic, so they act as buffers for the indoor humidity.

Many attempts have been made to model the indoor humidity condition. The attempts vary from simple steady state models that completely disregard the indoor moisture buffering (the Loudon model, 1971). Other are empirical models that acknowledge, but physically do not describe the buffering effect (Tsuchiya, 1980), and more physics based models that consider the buffering in a surface layer of the building elements (e.g. the Effective Moisture Penetration Depth model, Kerestecioglu et al., 1990). However, none of these models make it possible to predict the conditions deeper in the structures, and they often do not consider the non-isothermal conditions that normally exist between the indoor climate and the exterior building envelope. Consequently, there is a substantial interest to develop methods for synchronous prediction of humidity conditions of the indoor air, of the materials in the building envelope and in furnishing. For instance, such development is under way to complement the DOE *EnergyPlus* program (Crawley et al., 2000). However, *EnergyPlus* is based on a response factor method, which may have some difficulty in calculating transient moisture transfer, as this is a non-linear phenomenon (Liesen et al. 1999).

This paper will describe a Danish modelling activity that was started in 1998 with the overall purpose to develop an analytical tool for moisture conditions in buildings to investigate and optimise operational strategies for demand-controlled ventilation of buildings. The new model is based on a finite control volume method that is able to manage the non-linear conditions.

Moisture conditions cannot be predicted without knowing the thermal conditions. It is quite obvious therefore to develop the model for prediction of whole building moisture conditions as an extension to an existing tool for 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 already been validated, and they already have a user interface. One such program

is *tsbi5*, included in the Building Simulation tool *BSim2000* (Wittchen et al., 2000).

## BUILDING SIMULATION 2000

*BSim2000* is a user-friendly flexible computer program for analyses of indoor climate, energy consumption and daylight performance of buildings. *BSim2000* contains different tools and links to applications making it possible to carry out a complete thermal and daylight analysis of a building. 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 user interface of *BSim2000*.

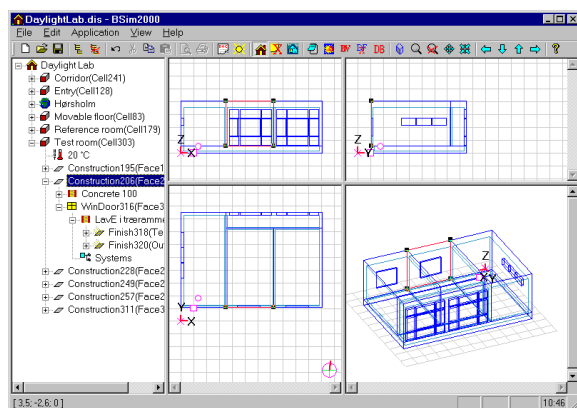


Figure 1 *BSim2000* model of the Daylight Laboratory at the Danish Building and Urban Research.

Applications integrated in *BSim2000* are:

- *SimView* for editing and visualization of the 3D building geometry.
- *XSun* for analyses of solar distribution and shadows in and around buildings.
- *tsbi5* for thermal simulations, which is an extended and improved version of *tsbi3* (Johnsen and Grau, 1994). The program 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).
- *SimLight* is a simple tool for estimation of the daylight conditions in a convex room.
- *SimDB* is the user interface for the common database with materials, constructions etc.

From within *SimView* it is possible to link to a few external programs:

- *SimDxf* allowing the user to create the geometry of the building model by using a CAD-drawing (DXF-format) as the basis (Grau and Wittchen, 1999).

- The *Bv98* program can import the building model from *SimView*, allowing to carry out a heating demand calculation according to the EN832 standard.
- The building model can be exported to Radiance for visualisation and detailed calculation of the lighting and daylighting conditions (Ward Larson, 1998).

The following calculations can be made on most buildings using *BSim2000*:

- Heat gains from solar radiation, people, lighting, and equipment
- Solar radiation through windows
- Heating, cooling and ventilation
- Power and energy balance
- Moisture balance
- Temperature conditions
- Heat and air exchange between zones
- Shading conditions
- Variable infiltration and venting
- Several different ventilation systems simultaneously
- Surface temperatures and condensation risks
- 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

*BSim2000* was released in May 2000 and is 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 utilisation of passive solar energy.

*BSim2000* can be executed on computers with the operating system Windows95/98/NT/2000.

## DATA MODEL

A building in *BSim2000* is seen as a collection of one or more rooms. A room is defined by the plane faces that separate the rooms from each other and from the outdoors. The faces define the geometry, and represent the location of constructions that are defined by

the thermophysical properties of their materials. A face may include a number of windows, doors and openings. One or more rooms can be included in a so-called thermal zone (or just "zone"), indicating that the rooms take part in a thermal simulation. To a zone can be attached different systems that have an influence upon or control the indoor climate. A "system" is a general concept, and not just a mechanical system like ventilation, lighting or heating and cooling systems, but may also represent the heat and moisture load from people, or air exchange with the outside or neighbour zones. In Figure 2 is shown the data model for a building as a NIAM diagram (Nijssen and Halpin, 1989).

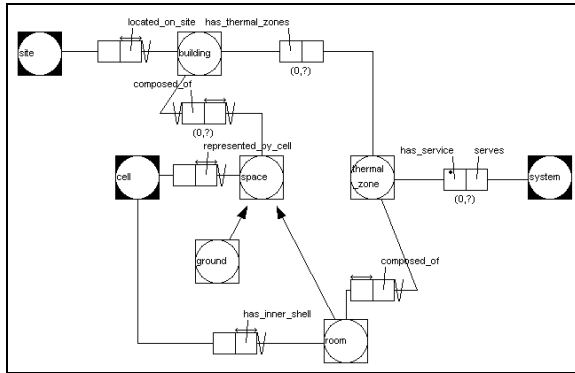


Figure 2 Bsim2000 data model of a building.

The common data model for *Bsim2000* consists of eight separate, but interrelated models of different aspects, e.g. a model for 3D geometry and topology. The models are defined as EXPRESS files, which have been automatically converted to C++ classes, on which the implementation of the program is based (Rode and Grau, 1995).

## MOISTURE MODEL

In the following is described the theoretical basis for dynamic calculation in *tsbi5* of the humidity conditions in rooms, constructions and furnishing.

A humidity balance equation 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 convective transfer between the zone air and the adjacent constructions and furnishing, 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. A dynamic calculation of moisture conditions is carried out for the interior of every single construction and furnishing. The zones on each side of the construction give the boundary conditions. Information is retained for each zone about the temperature  $T$  [°C] and the humidity ratio of the air  $x$  [kg/kg]. The air in a zone is considered as being fully mixed.

Constructions (and furnishing) are considered as composite building components consisting of several layers of building materials. Every material layer is again subdivided into one or several control volumes for which the calculations are carried out. A node point in the centre of each control volume represents the conditions in the whole volume, and a node point is placed on the two surfaces of the construction.

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

## HUMIDITY BALANCE FOR ZONE AIR

The following influences on the air's humidity condition 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 (mixing)

The humidity balance for zones is made up for the humidity ratio  $x$  [kg/kg] (mass of water vapour 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:

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

The humidity transferred between the construction surfaces 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, as complete mixing is supposed, it suppresses air 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:

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

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.

Moisture contributions from "systems" may originate from people or from other moisture loads in the zone. These systems' influences 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  $G_{syst}$ .

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 vapour content in the previous time step has been used in the recalculation between vapour pressure and vapour content of air on the left hand side of the equation.

## MOISTURE IN CONSTRUCTIONS

The model for moisture transport in the constructions considers moisture transport in the form of vapour diffusion. The moisture transport internally in the constructions is described in a transient way, i.e. by making allowance for each layer's moisture buffering capacity.

A calculation is carried out for each control volume and time step of how much moisture is induced by vapour diffusion, and how much is removed. The sum of these contributions gives rise to 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 vapour pressures. For the sake of numerical stability in all situations, an implicit calculation procedure is used in the model, as it will be described below.

Vapour diffusion into a control volume  $i$  from the adjacent element  $i-1$  is calculated from Fick's law. It is assumed that the two materials have individual water vapour permeabilities, and that the control volumes

have individual thickness. The vapour flux over the interface between the two control volumes in the time step from time index  $j$  to  $j+1$  is expressed as:

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

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

According to Equation 5 the vapour flux should be calculated from the vapour pressures at the end of the time step. However, when the calculation has arrived at time level  $j$ , and the conditions are to be calculated for the next time step, the conditions at time level  $j+1$  are not yet known. Thus, the values for the vapour pressures on the right hand side of the equation cannot just be inserted explicitly. Instead, the following procedure will be followed.

Throughout the time step, the implicitly indicated vapour flux from Equation 5 is assumed to be constant, and the increase in moisture content for control volume  $i$  can be expressed as follows:

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

By expressing the change in moisture content as a change in the relative humidity (of the air in the pores of the material) multiplied by the specific moisture capacity (slope of the material's sorption curve), and by inserting the expressions for  $g$ , the following expression can be set up:

$$(\rho \xi)_i \Delta s_i \frac{\phi_i^{j+1} - \phi_i^j}{\Delta t} = \frac{p_{i-1}^{j+1} - p_i^{j+1}}{\frac{\Delta s_{i-1}}{2 \delta_{i-1}} + \frac{\Delta s_i}{2 \delta_i} + Z_i} + \frac{p_{i+1}^{j+1} - p_i^{j+1}}{\frac{\Delta s_i}{2 \delta_i} + \frac{\Delta s_{i+1}}{2 \delta_{i+1}} + Z_{i+1}} \quad (7)$$

The calculation procedure now follows the sequence 1 – 3:

(1) For the relative humidity is used the ratio between vapour pressure,  $p$ , and saturation vapour pressure,  $p_s$ . Equation 7 can then be written in vapour pressure alone:

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

The boundary node  $i=1$  is at surface 1 of the construction and is calculated without thickness ( $\Delta s_i=0$ ). The

following equation expresses the vapour flow balance over this node:

$$0 = \beta_{surface1} (p_{air} - p_1^{j+1}) + \frac{p_2^{j+1} - p_1^{j+1}}{\frac{\Delta s_2}{2\delta_2} + Z_2} \quad (9)$$

A similar equation is set up for the boundary  $i=n$  at surface 2, and the whole equation system is solved simultaneously for all  $p_i$ 's.

(2) Since the whole problem is non-linear (because the moisture capacity is not a constant value), a special procedure is followed to ensure correct mass balances. The vapour pressures just found are regarded as preliminary predictions of the new values. The preliminary vapour pressures are used in the moisture balance of each control volume. By employing Equation 5 and 6, the new moisture contents are found for each control volume.

(3) Finally, the equilibrium relative humidity is determined for each control volume by using the calculated moisture content and the sorption curve for the relevant material.

## MATERIAL DATABASE

*Tsbi5*'s database of building materials has been extended with moisture properties:

- Sorption and desorption curves giving the moisture content  $u$  (kg/kg) of the relative humidity
- Vapour permeability depending on relative humidity (or moisture content)

Figure 3 illustrates the user interface of the database.

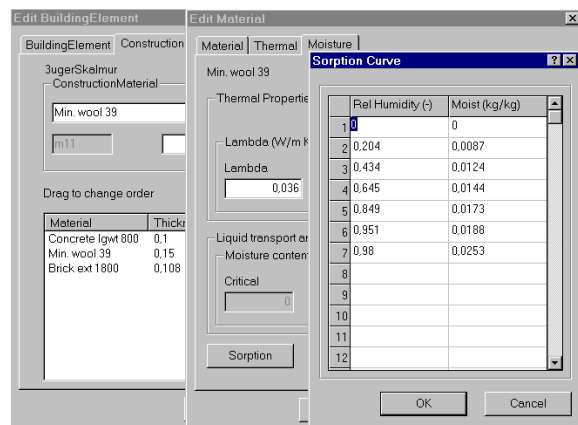


Figure 3 Definition of a construction with three material layers, and presentation of points for the sorption curve of a layer of mineral wool.

## VALIDATION

Calculations with the moisture model in *BSim2000* are compared with measurements in a test cell in

Rode et al., 2001. The test cell is a full-scale test chamber for measuring the moisture buffer effect of spaces and building envelope components. For this purpose, equipment for humidifying and desiccating the cell is installed within the cell. The moisture conditions in the cell are studied when it is furnished with different building materials, and their moisture buffering effect is investigated.

## EXAMPLE

In the following is given an example of a simulation with *tsbi5* of a typical Danish single-family house. The house will be simulated both with and without using the described new model for moisture absorption, and the results will be compared. Simulations without the moisture absorption model are simple steady state calculations of the moisture balance of the room considering the release of moisture from activities in the rooms and its dilution by the air change.

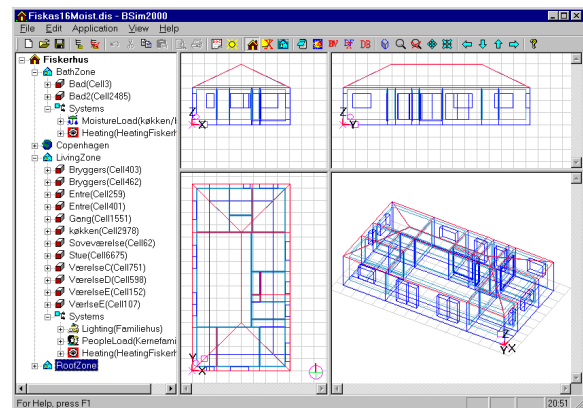


Figure 4 The single-family house shown in SimView.

The house (see Figure 4) consists of a number of rooms for different functions: Living room, kitchen, entrance, sleeping room, two bathrooms etc., and an attic. Rooms with similar functions have been collected in the following three thermal zones: *RoofZone* with just the attic, *BathZone* with the two bathrooms, and *LivingZone* with all other rooms.

Systems attached to the thermal zones are:

- *RoofZone* has infiltration (1.2 ach).
- *BathZone* has moisture load in the morning, in the afternoon and late evening during workdays. The bathrooms are heated in the heating season but with night-setback. The base infiltration is 0.5 ach, but augmented 4 times when there is a moisture load.
- *LivingZone* has heating in the heating season, lighting and is occupied by 3.5 persons. The infiltration is 0.5 ach.

The constructions are:

- Outer walls are made of 0.10 m lightweight concrete, 0.15 m mineral wool, and 0.108 m brick facing the outdoors (see Figure 3)
- Inner walls are made of 0.10 m lightweight concrete
- Floors are made of 0.005 m linoleum, 0.1 m concrete, 0.125 m polystyrene and 0.2 m light weight expanded clay (facing the ground)
- Roofs are made of 0.016 m pine boards (as ceiling), a vapour barrier, 0.022 m wood and 0.3 m mineral wool.

The house is located in Denmark, and for the simulations are used weather data from the Danish Design Reference Year.

Two simulations have been performed for one year – either with or without using new moisture model. The results of the predictions of indoor relative humidity are shown in Figures 5 and 6.

The model predicts plausible levels for the indoor humidity in various zones over the year, e.g. for a building located in the Danish climate, around 60% RH in summer and around 30% RH in winter. The model also predicts the daily variations of humidity. This is particularly interesting for special rooms, like the bathrooms, where the moisture loads are very high for short moments every day.

Most remarkably, the results also clearly show that the daily variations of the relative humidity become significantly smaller when the calculations consider the moisture absorption effect of materials adjacent to the indoor climate. However, it must be reported that the calculation shown in this paper does not consider paint on the walls in the building – this would otherwise have reduced the effect of the materials' moisture buffer capacity. Counting in the other direction, it must be mentioned that the indoor spaces are simulated as being unfurnished.

Finally, it must be emphasized that so far no validation has been carried out of the model's prediction of indoor humidity variation for a complex building, like in this example. The example is simply meant to illustrate the computational capabilities. Validation against simpler test cell data is under way (Rode et al. 2001).

Figure 7 illustrates the calculated relative humidity at interior and exterior interfaces of materials in one of the walls of the building as it varies over one year. A transient calculation with *Tsbi5* of the humidity distribution in an envelope construction has been compared with good results against predictions with another validated tool for envelope moisture calculations (Rode et al. 2001).

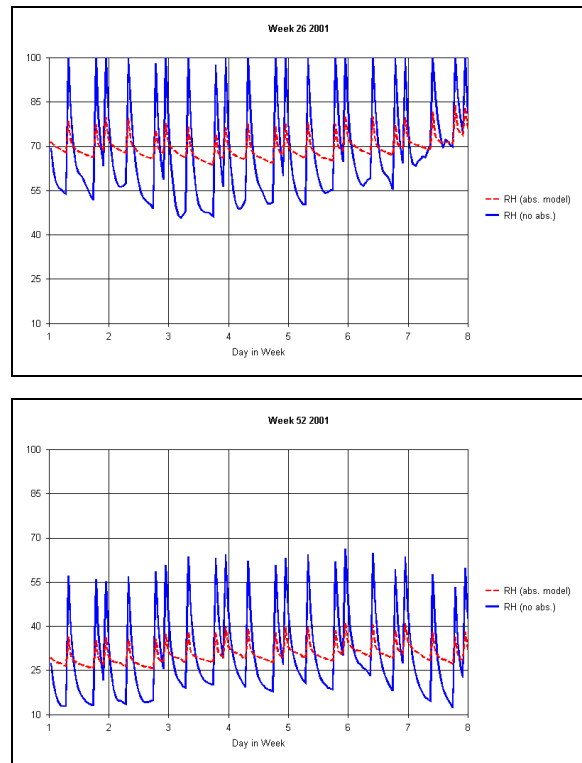


Figure 5 Relative humidity in BathZone simulated with the moisture model (abs. model) and without (no abs.), shown for a week of June and a week of December.

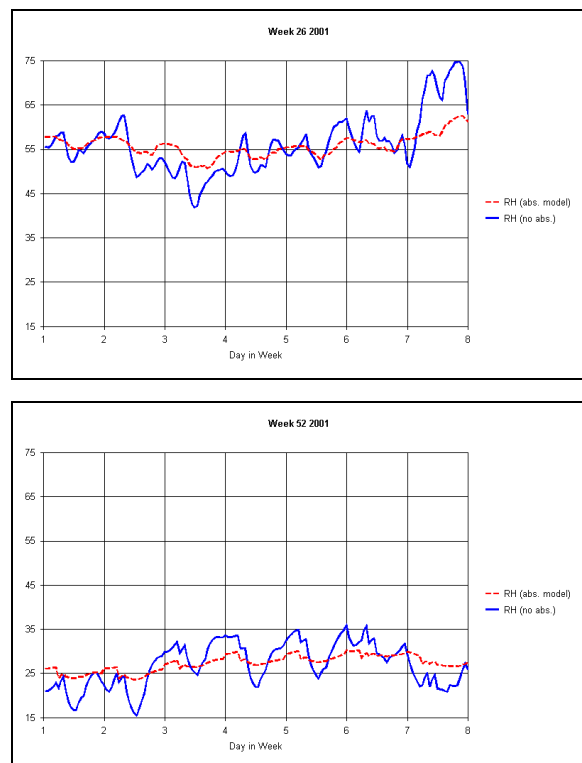


Figure 6 Relative humidity in LivingZone simulated with and without the moisture model, shown for a week of June and a week of December.

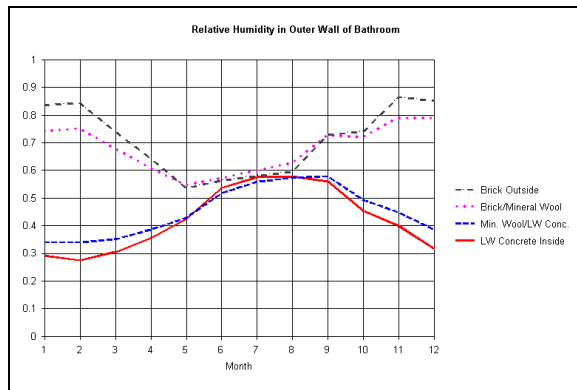


Figure 7 One year's relative humidity variation in one of the exterior walls simulated with the model that considers transient moisture accumulation in the building constructions.

## CONCLUSIONS

By extending an existing computer tool for dynamic thermal simulation of buildings with a model for moisture release and uptake in building materials and furnishing is demonstrated a potential to make more accurate predictions of indoor humidity variations. Synchronously, a transient calculation of the moisture conditions of the materials in the building envelope is carried out. Since the moisture conditions in building constructions depend very much on the indoor humidity condition, and since the building envelope and furnishing also influence the indoor humidity, it is anticipated that the new development will result in improved simulations of moisture conditions both for the indoor air and for the building constructions.

There is no substantial overhead of running these combined simulations, so they can easily be implemented in existing thermal simulation programs. The paper has documented the implementation of the moisture model in a thermal simulation tool, and given an example of the use of the model.

Validation of the new moisture model is under way, and has begun with comparison against measurements in an outdoor test cell furnished with single materials.

## ACKNOWLEDGEMENTS

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## NOMENCLATURE

$A$	area, m <sup>2</sup>
$G$	rate of induced humidity to the air, kg/s
$g$	vapour flux, kg/m <sup>2</sup> s
$i$	index for space
$j$	index for time
$n$	air change by ventilation, s <sup>-1</sup>
$p$	partial pressure for water vapour, Pa
$u$	moisture content, kg/kg
$V$	volume, m <sup>3</sup>
$x$	humidity ratio, kg/kg
$Z$	vapour diffusion resistance, m <sup>2</sup> sPa/kg
$\beta$	convective moisture transfer coefficient, kg/(m <sup>2</sup> Pa s)
$\Delta s$	width of control volume, m
$\Delta t$	time step, s
$\delta$	water vapour permeability, kg/(m s Pa)
$\varphi$	relative humidity, -
$\rho$	density, kg/m <sup>3</sup>
$\xi$	specific moisture capacity, kg/kg