Calculation tool for whole building

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Rode, Carsten; Sørensen, Karl Grau

Calculation Tool for Whole Building Hygrothermal Analysis

Carsten Rode, Associate Professor, PhD*
Karl Grau, Senior Researcher, MSc+

1. 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.

Several attempts have been made to model the indoor humidity condition. References to some of these attempts are given by Wang (2000) and by Rode et al. (2001a).

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 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 already have a user interface. One such model is *tsbi5*, which is included in the integrated building simulation tool *BSim2000* (Wittchen et al., 2000).

2. BUILDING SIMULATION 2000

BSim2000 is a computational design tool for analysis of indoor climate, energy consumption and daylight performance of buildings**.** *BSim2000* integrates different computer models that make 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 *BSim2000.*

The following computational analyses 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
- Steady state moisture balance

* Technical University of Denmark, Department of Civil Engineering, Building 118, Brovej, DK-2800 Kgs. Lyngby, Denmark.
+ Danish Building and Urban Research, P.O. box 119, DK-2970 Hørsholm, Denmark.

- 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

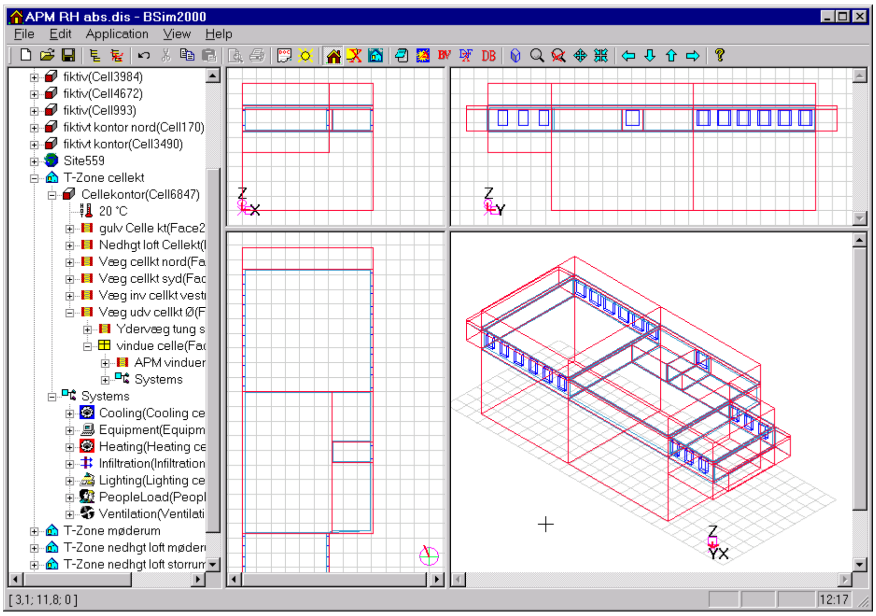

Figure 1 User interface for the model editor *SimView* in *BSim2000*.

3. WHOLE BUILDING MOISTURE MODEL

A new transient moisture model for the whole building - its indoor climate and its enclosure - has been developed as an extension to the other models in *BSim2000*. A building is seen by *BSim2000* 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 convective transfer between the zone air 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.

Simultaneously, calculations of transient moisture conditions are carried out for all interior and exterior constructions of the building. The zones on the sides of the constructions give the boundary conditions.

3.1 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 [°C] and the humidity ratio of the air x [kg/kg]. The air in a zone is considered as being fully mixed, or with some possibility to approximate the stratification in the zones (Brohus et al. 2000).

The constructions consist of one or more layers of building material that are characterised 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 centre of the control volumes, and there are node points placed on the two surfaces of the construction. Furnishing may be considered as interior building constructions that face the same zone of both sides, or which are calculated from one side to an adiabatic, vapour tight centre.

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

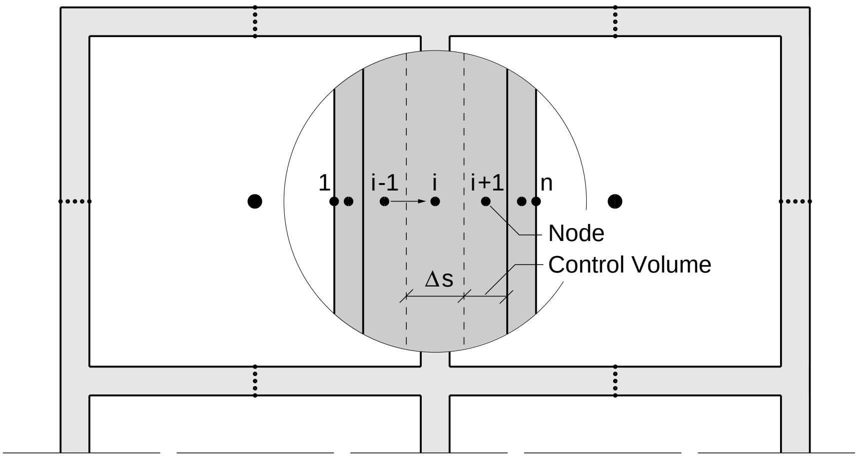

Figure 2 Part of a plan of a building as understood by *BSim2000* with two of its zones and an enlarged view of a wall that separates the two zones. The figure indicates the location of node points for the numerical calculation.

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 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.

3.2 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:

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

where ΣG on the right-hand side represents the sum of moisture sources in a zone. Characteristic groups of moisture sources are described in the following.

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

$$G_{constr} = \sum_{constructions} A_{surf}\,\beta\left(p_{surf} - p_{air}\right) \qquad (2)$$

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:

$$G_{vent} = \sum_{air\,sources} n_{vent}\,V\,\rho\left(x_{vent} - x_{air}\right) \qquad (3)$$

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 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. 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:

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

$$x_{air}^{old} + \frac{\Delta t}{V\rho_{air}}\sum_{constr} A_{surf}\,\beta\,p_{surf} + \Delta t \sum_{air\ sources} n_{vent}\,x_{vent} + \frac{\Delta t}{V\rho_{air}}G_{syst}$$

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.

3.3 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 considering each layer's moisture buffering capacity.

A calculation is carried out for each control volume and time step of the balance between moisture gained and lost by vapour diffusion, and how much is removed. 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 vapour pressures. For the sake of numerical stability in all situations, an implicit calculation procedure is used in the model.

Vapour 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 vapour permeability, and the control volumes may 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:

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

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, δ, is determined for each control volume as a function of local moisture content.

Vapour fluxes calculated like 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:

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

As indicated by the time index *j+1* for the vapour pressures and fluxes in equations 5 and 6, the procedure is implicit, i.e. set up on the basis of yet unknown vapour 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) equations need closure by coupling the moisture content and vapour pressure through the sorption curves of the materials. How this is solved in *BSim2000* is shown in more detail by Rode et al. 2001a.

4. VALIDATION

Calculations with the moisture model in *BSim2000* are compared with measurements in a test cell. The test cell (see Figure 3) is a full-scale, outdoor test chamber for measuring the moisture buffer effect of spaces and building envelope components. The test cell is an existing apparatus that was used in the European PASSYS project (European Commission, 1994) for thermal testing. The test cell itself is very well insulated with 40-50 cm of insulation on all sides, and steel sheets on the inside and outside that make the construction inert to moisture flow. The exchangeable southern facade has been filled with a wall with 30 cm of insulation and a polyethylene vapour retarder facing the indoor air.

The moisture conditions in the cell are studied when it is furnished with different building materials, and their moisture buffering effect is investigated. Equipment for humidifying and desiccating the cell is installed within the cell, and this equipment was operated in interchanging cycles with 12 hours of humidification followed by 12 hours of drying of the indoor air. The indoor relative humidity was monitored for controlled rates of moisture release or removal to/from the air, while different materials were installed in racks within the test cell. Further descriptions of the experiments can be seen in another paper in these proceedings (Rode et al., 2001b). The results have been compared against computer simulations with *BSim2000*, and the results are shown in Figure 4. Results for more materials are shown in (Rode et al., 2001b).

Figure 3 Photo of two PASSYS test cells at the Technical University of Denmark, one of which is used for the validation of *BSim2000*'s moisture model.

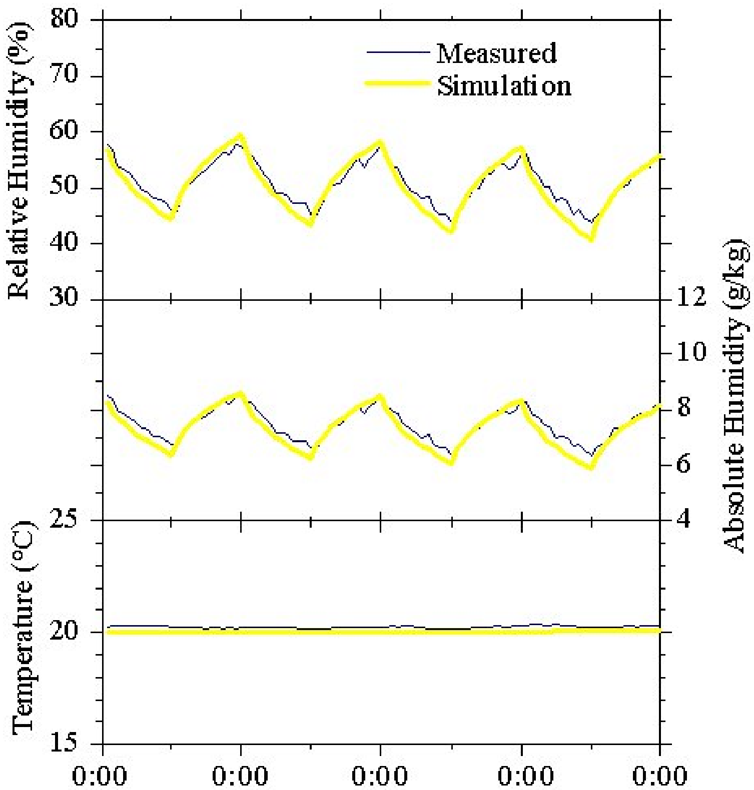

Figure 4 Measured and calculated humidity in the PASSYS test cell when 3 m^2 of cellular concrete was put in the cell and humidity was produced and withdrawn interchangeably at rates of 200 g / 12 hours.

5. PRACTICAL USE OF THE MODEL

During the autumn 2001 the moisture model in *BSim2000* has been 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 the chilled ceiling, and in general to estimate the indoor air quality.

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

The consulting firm's main conclusions after the testing are:

The new moisture model will provide possibility to:
- Study the relative humidity in rooms taking into account the ability of building materials and furniture to absorb and desorb moisture.
- Analyse the moisture level of constructions.
- Analyse energy consumption in relation to construction moisture in building elements.
- Analyse 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.

6. CONCLUSIONS

An existing computer 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 should be possible to make more accurate predictions of indoor humidity variations. Simultaneously, complete transient calculations are carried out of the moisture conditions within all 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 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 given a brief description of how the moisture model has been implemented in a thermal building simulation tool, and some examples are referred of the practical use of the model as a design tool for consultants.

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.

7. ACKNOWLEDGEMENTS

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9. NOMENCLATURE

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