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THE HYGROTHERMAL BEHAVIOUR OF ROOMS: COMBINING THERMAL BUILDING SIMULATION AND HYGROTHERMAL ENVELOPE CALCULATION

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ABSTRACT

The hygrothermal behavior of a building component exposed to weather is an important aspect of the overall performance of a building. Today the hygric transport phenomena through a building envelope are well understood and a realistic assessment of all relevant effects can be carried out by one of the numerous models and computer programs, that have been developed in different countries over the last years. The calculation of the hygrothermal performance of a part of the envelope is state-of-the-art, but until now, the total behaviour of the actual whole building is not accounted for. Its importance is increasing as modern dwellings become more airtight and show elevated indoor humidity levels. This requires the detailed consideration of all hygrothermal interactions between the indoor air and the envelope. In this paper a new holistic model, that takes into account the main hygrothermal effects, like moisture sources and sinks inside a room, moisture input from the envelope due to capillary action, diffusion and vapor ab- and desorption as a response to the exterior and interior climate conditions, heat source and sinks inside the room, heat input from the envelope, the solar energy input through walls and windows and hygrothermal sources and sinks due to natural or mechanical ventilation will be presented.

INTRODUCTION

How much ventilation and additional heat energy is required to ensure hygienic indoor conditions when a building contains construction moisture? What will happen to the hygrothermal behavior of walls and ceiling when a historic cellar is turned into a discotheque or restaurant? How do the indoor air conditions and the envelope of buildings with temporary occupation react to different heating and ventilation strategies? Can sorptive finish materials improve human comfort? These questions can either be answered with the help of experiments [Künzel 1965,Künzel 1988] or by numerical simulations. In view of the fact that experiments are often time-consuming and, in some cases, both problematic and expensive intensive work has been done over the past few years on the development of mathematical approaches and procedures to evaluate the real hygrothermal performance of the whole building. During the last years several models for calculating the thermal behavior of a building were developed. The application of programs like ESP-r, TRNSYS, DOE-2 and EnergyPlus is a standard for designer. A good overview of building simulation tools can be found on the webpage of U.S. Department of Energy (http://www.eren.doe.gov/buildings/tools_directory)

Nevertheless, most of the commonly used thermal building simulation tools treat the moisture exchange with the envelope in a simplified manner by assigning a certain moisture storage capacity to the interior of the building. This approach is often sufficient as long as average humidity conditions are the only concern. However, if the exact indoor humidity fluctuations or the moisture profiles in the building envelope are relevant new models that combine the thermal building simulation with the hygrothermal component simulation have to be developed.

COMBINING THERMAL BUILDING SIMULATION AND HYGROTHERMAL ENVELOPE CALCULATION

As mentioned before there are a number of validated models for thermal building simulations as well as hygrothermal envelope calculations used in building practice today. However, working combinations of these models are not yet available for the practitioner. In principle, this combination is done by coupling existing models of both types. Figure 1 shows the concept of such a combination where balance equations for the interior space and the different envelope parts have to be solved simultaneously. Recently the first real hygrothermal simulation models have been developed [Karagiozis et al. 2001,Rode et al. 2001]but so far only limited validation cases have been reported. The model employed in this paper is called WUFI+ [Holm et al.

2002] and is based on the hygrothermal envelope calculation model WUFI [Künzel 1994].

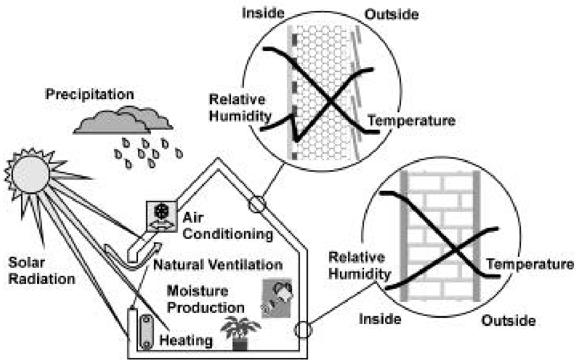

Figure 1: Coupling concept for the simultaneous treatment of the hygrothermal effects of interior heat and moisture loads, exterior climate and transient behavior of envelope components.

Governing Equations

For the coupled heat and mass transfer for vapor diffusion, liquid flow and thermal transport in the envelope parts the model solves the following equations

Energy conservation

$$\left(rc+\frac{\P H_w}{\P q}\right)\cdot\frac{\P q}{\P t}=\nabla\cdot\left(l\nabla q\right)+h_v\nabla\cdot\left(d_p\nabla\left(jp_{sat}\right)\right) \quad (1)$$

Mass conservation

$$\frac{dw}{dj}\cdot\frac{\P j}{\P t}=\nabla\cdot\left(D_w\frac{dw}{dj}\nabla\Phi+d_p\nabla\left(\Phi p_{sat}\right)\right) \quad (2)$$

where

ϕ = relative humidity, [-]
t = time, [s]
θ = temperature, [K]
c = specific heat, [J/kgK]
w = moisture content, [kg/m³]
p_{sat} = saturation vapor pressure, [Pa]
? = thermal conductivity, [W/(mK)]
H = total enthalpy, [J/m³]
D_ϕ = liquid conduction coefficient, [kg/ms]
δ_p = vapor permeability, [kg/(msPa)]
h_v = latent heat of phase change, [J/kg]

On the left-hand side of equation (1) and (2) are the storage terms. The fluxes on the right-hand side in both equations are influenced by heat as well as moisture: the conductive heat flux and the enthalpy flux by vapor diffusion with phase changes in the energy equation strongly depend on the moisture fields and fluxes. The liquid flux in the moisture transport equation is only slightly influenced by the temperature effect on the liquid viscosity and consequently on D_ϕ. The vapor flux, however, is simultaneously governed by the temperature and the moisture field because of the exponential changes in the saturation vapor pressure with temperature.

Equations (1) and (2) must be solved for every part of the envelope individually. Beside the exact definition of the assembly, including the material properties, the corresponding interior and exterior climatic boundary conditions are required. Usually the exterior boundary parameters are well known. On the other hand the interior climate conditions are influenced by the exterior conditions, the type of usage of the room and the ab-/desorption capacity of the interior walls and furnitures.

Heat balance of the room:

Due to the fact that energy simulations are widely used the thermal governing equations will not explained in detail. The indoor room temperature θ_i is linked to the heat fluxes into the room. This means that not only the heat flux over the envelope (transmission and solar input) is important. In addition, internal thermal loads and the air exchange due to natural convection or HVAC systems must be taking into account. The energy balance can be described with the following equation.

$$\begin{aligned} r\cdot c\cdot V\cdot\frac{dq_i}{dt} &= \sum_j A_j a_j(q_j-q_i)+ \\ &\dot{Q}_{Sol}+\dot{Q}_{il}+ \\ &n\cdot V\cdot r\cdot c\cdot\left(q_a-q_i\right)+\dot{Q}_{vent} \end{aligned} \quad (3)$$

where:

ρ = density of the air, [kg/m³]
α_j = heat transfer coefficients [W/m^{2}K]
θ_a = exterior air temperature, [K]
θ_j = surface temperature, [K]
θ_I = indoor air temperature, [K]
t = time, [s]
A_j = surface area, [m²]
c = heat capacity of the air [J/kgK]
n = air change per hour, [h^{-1}]
$\dot{Q}_{sol}$ = solar input which leads directly to an increase of the air temperature or furniture, [W]
$\dot{Q}_{il}$ = internal gains such as people, lights and equipment, [W]
$\dot{Q}_{vent.}$ = heat fluxes gained or lost due to ventilation, [W]
V = volume, [m³]

Moisture balance of the room:

The moisture condition in the room are a consequence of the moisture fluxes over the interior surfaces, the user dependent moisture production rate and the gains or loses due to air infiltration, natural or mechanical ventilation as well as sources or sinks due to HVAC systems.

$$V \cdot \frac{dc_i}{dt} = \sum_j A_j \dot{g}_{w\,j} + n \cdot V(c_a - c_i) + \dot{W}_{IMP} + \dot{W}_{Vent} + \dot{W}_{HVAC} \qquad (4)$$

where:

c_a	= absolute moisture ratio of the exterior air, kg/m³
c_i	= absolute moisture ratio of the interior air , kg/m³
$\dot{g}_{w\,j}$	= moisture flux from the interior surface into the room, kg/(sm²)]
$\dot{W}_{IMP}$	= moisture production, kg/h
$\dot{W}_{vent}$	= moisture gains or loses due to ventilation, kg/h
$\dot{W}_{HVAC}$	= moisture gains or loses due to the HVAC system, kg/h.

For each part of the envelope, the surface temperatures and moisture conditions, respectively the surface thermal and moisture fluxes are solved using equations (1) and (2). The required indoor conditions can be derived from equation (3) and (4). Because of the strong coupling of the two sets of equations the resulting indoor room temperature and relative humidity are determined iteratively.

COMPARISON WITH OTHER MODELS

For a typical application case, the results from WUFI+ with those from TRNSYS will be compared. Therefore, the thermal behavior of a two-story building made out of prefabricated AAC elements will be simulated. It is assumed that the air exchange within the building is perfect and therefore the whole building can be simulated with a one-zone model.

The building with height of 6.5 m and 1625 m³ volume has a length of 20 m in east-west orientation and 12.5 m in north-south orientation. The building is designed without a basement. The flat roof is made out of concrete with a 180 mm thick insulation layer. The façade elements are made out of 36.5 cm thick AAC block work with an exterior mineral stucco and a gypsum plaster on the interior surface. On the south orientated façade 50 m² of windows are integrated, 20 m² on the other three facades. The U_w-value of the windows is assumed to be 1.4 W/(m²K) with a the total solar energy transmittance of 0.56. Table 1 shows for all building parts the geometrical set-up. The material properties are taken from the WUFI database [Künzel et al. 2001].

Table 1: geometrical setup of the building

	area [m²]	assembly
exterior facade	S: 80 N: 110 W: 61,25 E: 61,25	-20 mm mineral stucco (water repellent, s_d-value: 0,2 m) -365 mm AAC -15 mm gypsum plaster
windows	S: 50 N: 20 W: 20 E: 20	-u-value: 1.4 W/mK -total solar energy transmittance: 0.56 -framing: 15 %
flat roof	250	-gravel -180 mm insulation -roof membrane V13 -200 mm concrete -15 mm gypsum plaster
floor	250	-60 mm cement screed -80 mm insulation -bituminous seal -160 mm concrete
ceiling	250	-60 mm cement screed -30 mm insulation -180 mm concrete -15 mm gypsum plaster
supporting wall	100	-15 mm gypsum plaster -150 mm concrete -15 mm gypsum plaster
room dividing wall	160	-20 mm gypsum board -50 mm mineral wool -40 mm air layer -20 mm gypsum board

The starting point is the beginning of the year with an initial moisture content corresponding to 80 % relative humidity. The hygrothermal behaviour is simulated over a period of one year. Hourly weather data measured in a typical year in Holzkirchen represent the climatic conditions. The infiltration rate is described with a constant ACH of 0.3 h^{-1}. The daily schedule of the moisture production rate can be seen in Figure 2. The total thermal load per hour is 1.2 kW. The comfort range for the interior humidity lies between 40 and 60 % RH with a maximum temperature of 27 °C.

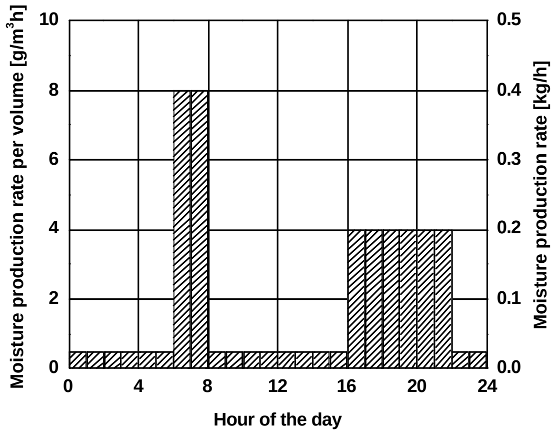

Figure 2: Daily time schedule of the moisture production rate in the test rooms.

Figure 3 shows the direct comparison of the calculated energy for heating and the resulting room temperature. The results from WUFI+ and TRNSYS corresponds well. The total energy use for heating computed by WUFI+ is amount to 56 kWh/m²a which is only ca. 2 % below the result from TRNSYS. This minor deviation is considered acceptable for such calculations according to [VDI 2001,Gertis et al. 1988,Stricker et al. 1989].

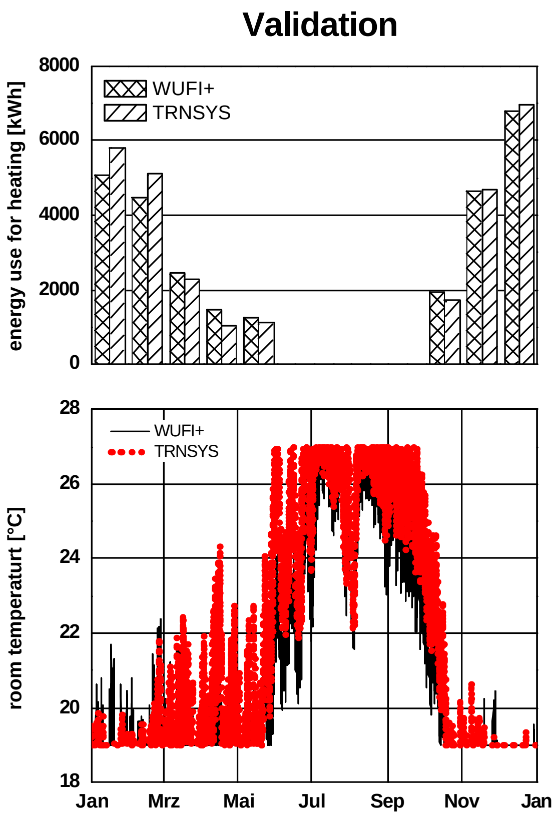

Figure 3: With WUFI+ and TRNSYS calculated energy use for heating and the resulting room temperature.

So far only the thermal part of it has been validated by comparing its results with those of well-established building simulation tools, but an important issue is the validation of these models by real life experiments carried out under well defined boundary conditions. The validation of the hygric part will be done within the frame of the experiments described below.

EXPERIMENTAL VALIDATION

The experiments are carried out in a building erected on the IBP test site in the 80s designed for energetic investigations published in [Künzel 1984]. Two of the five test rooms can be used for our purpose because they have identical walls. The ground plan of the test rooms and the adjacent spaces is plotted in Figure 4. The test rooms have a ground area of 20 m² and a volume of 50 m³. They are heavily insulated (200 mm of polystyrene) towards the ground. In order to avoid moisture flow to or from the ground the floor has a vinyl covering. The outer surfaces of the ceiling and interior wall sections are surrounded by a conditioned space. The external walls consist of 240 mm thick brick masonry with 100 mm exterior insulation (ETICS/EIFS). On the interior surface 12 mm of standard plaster is applied. The double-glazed windows are facing south (U-value: 1.1 W/mK, total solar energy transmittance: 0.57, frame ratio: 30 %). Special considerations is given to the air tightness of the rooms. Blower-door tests confirm a n_{50} value below 1 h^{-1}. Following IBP-investigations in the past reported in [Hens 1995] the walls and ceiling of one room (test room) is covered with aluminum foil while the other room is left as it is (reference room). Since the envelope of the test room has almost no sorption capacity it can be used to determine the moisture buffering effect of furniture and especially devised sorptive building components. The reference room with its plastered walls serves as an example for a typical construction of German houses.

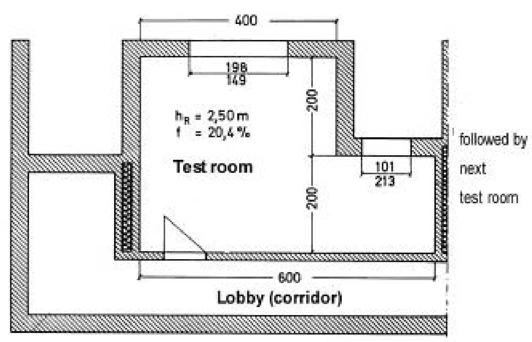

Figure 4: Ground plan of the test room.

The rooms are equipped with calibrated heating, ventilation and moisture production systems as well as fans in order to avoid stratification. The indoor air temperature and humidity is measured at different levels above the ground. Temperature sensors and heat flux meters are also fixed to the interior surface of external walls. All values are measured on a five minute basis and can be analyzed with an internet-based tool developed by IBP called IMEDAS (see Figure 5).

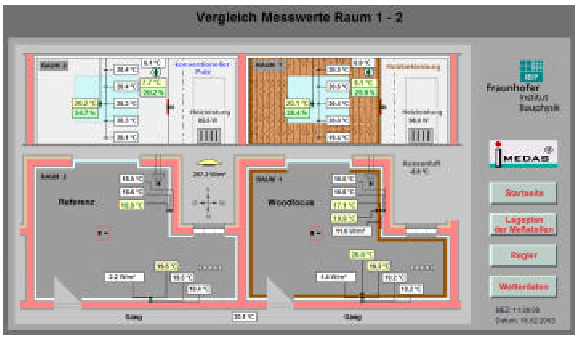

Figure 5: Screen shot of the internet-based visualization tool IMEDAS.

The first tests are done with a constant air change rate of 0.5 h^{-1} which is the hygienic minimum rate according to German regulations. The indoor air temperature will also be kept constant at 20 °C controlled by a sensor in the middle of the room. The moisture production is derived from an average moisture load of 4 g/m³. This means the total amount of water dissipated in the room per day is 2.4 kg or 48 g/m³. In reality the production rate will not be constant over the whole day. Here a basic production rate of 0.5 g/m³h is assumed with peaks in the morning and in the evening, i.e. 8 g/m³h from 6°° to 8°° a.m. and 4 g/m³h from 4°° to 10°° p.m. every day. (Figure 2)

RESULTS

The measured values for the relative humidity in both test rooms are plotted in Figure 6. The corresponding calculations in Figure 7 are based on the assumptions as described above concerning indoor temperature, moisture production and ventilation. They are carried out for the test room in its original form (i.e. covered with aluminum) and the reference room, which is lined with the standard gypsum plaster. In order to achieve a dynamic equilibrium of the moisture conditions in the rooms the outdoor air conditions are kept constant during the calculation period. They are set to -5 °C and 80 % R.H. without considering solar radiation or long wave emission for simplicity reasons. The simulations are carried out with a constant air change rate of 0.3 and 0.5 h^{-1}. The resulting evolutions in relative humidity of the interior air for the two test rooms with the different ventilation rates are plotted in Figure 7.

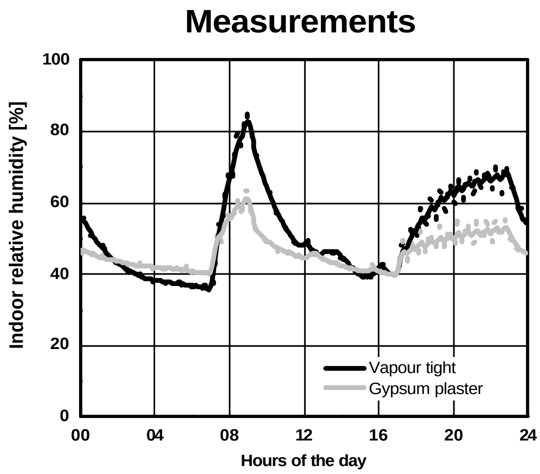

Figure 6: Measured relative humidity inside the two test rooms.

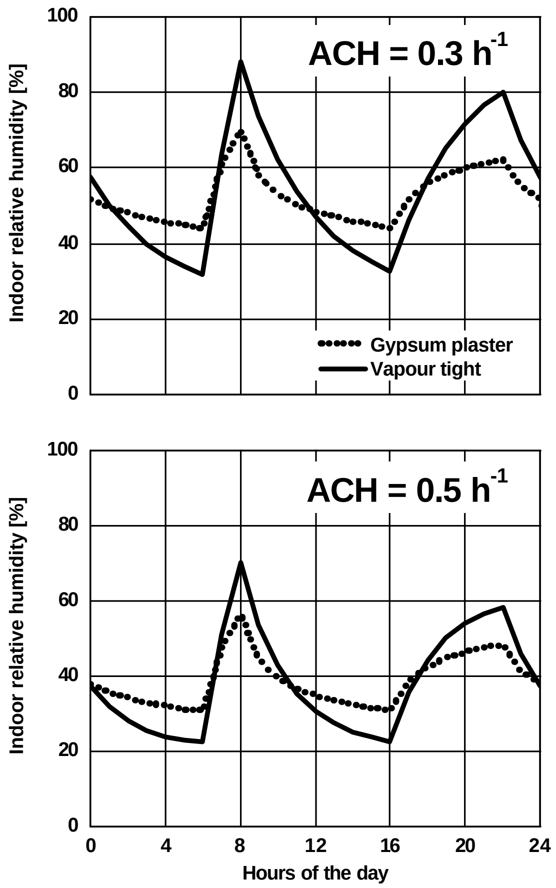

Figure 7: Resulting relative humidity inside the two test rooms assuming different air change rates (ACH) calculated with WUFI+.

The direct comparison of the measured and the calculated indoor relative humidity shows a good agreement. One of the reasons why the simulated results are not exactly identical with the measurements is, that for the simulation the exterior temperature is kept constant without considering solar radiation or long wave emission. An additional source of error is that the humidifier work in an on/off mode in order to supply the defined moisture load.

The measurements and the two simulations carried out with different ACH rates show, as expected, a greater fluctuation of the indoor air humidity without the sorption capacity of the interior plaster. For an ACH of 0.5 h^{-1} which is the hygienic minimum rate according to German regulations the peaks during extensive moisture production can be reduced from 70 % to about 50 % RH. The mean RH over the 24-hour period lies in both cases around 40 %, a realistic value for the indoor air conditions in dwellings during wintertime. In the case of ACH = 0.3, the indoor air humidity without sorption capacity of the envelope exceeds 80%. The buffering effect of the plaster is here even more pronounced especially during the extended moisture production.

CONCLUSIONS

The hygrothermal behavior of the building envelope has an important effect on the overall performance of a building. Therefore, combined tools for hygrothermal envelope calculations and whole building simulations are being developed in several places. Since there are hardly any experimental investigations suitable for the validation of these new models, the examinations described here will help to fill this gap. The first results show that the indoor air-humidity conditions are strongly influenced by the ventilation rate and surface conditions.

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