Predicting Indoor Temperature and Humidity Conditions Including Hygrothermal Interactions with the Building Envelope

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ABSTRACT: The hygrothermal behaviour of the building envelope affects the overall performance of a building. There are numerous tools for the simulation of the heat and moisture transfer in the building envelope and also whole building simulation tools for energy calculations. However, working combinations of both models for practical application are just about to be developed. In this paper such a combined model, that takes into account moisture sources and sinks inside a room, input from the envelope due to capillary action, diffusion and vapour ab- and desorption as a response to the exterior and interior climate conditions as well as the well-known thermal parameters will be explained. By way of well documented field experiments the new model is validated and the moisture buffering capacity of the building envelope is determined. In the conclusions the possible range of future applications of hygrothermal building performance models is addressed and demands for further research are indicated.

KEYWORDS: HYGROTHERMAL SIMULATIONS, INDOOR HUMIDITY, MOISTURE BUFFERING, INTERMITTENT AIR-CONDITIONING, HUMIDITY CONTROL.

1 INTRODUCTION

The heat and moisture behaviour of the building envelope is an important aspect of the overall performance of a building. Today the hygrothermal transport phenomena through a building enclosure exposed to natural climate conditions are well understood and a number of models and computer codes have been developed and validated worldwide [Trechsel et al. 2001]. The same holds for thermal whole building simulations where a wide range of validated computer codes exists, e.g. ESP-r, TRNSYS, DOE-2 and EnergyPlus. However, very few models consider all hygrothermal interactions between the indoor air and the building envelope in detail. A number of questions, which have gained importance lately, require a more accurate consideration of the hygrothermal processes in the building envelope, e.g.:

- How much ventilation and additional heating or cooling energy is required to ensure hygienic indoor conditions when a building contains construction moisture or has been flooded?
- What happens to the building envelope when the indoor environment of a historic building is severely changed e.g. by turning it into a laundry or restaurant?
- How do different envelope components react to fluctuating indoor air conditions of buildings with temporary occupation?
- What humidity control strategies should be employed to preclude mould formation on the external and internal surfaces of the building envelope?
- Can vapour absorbing finish materials help to save energy and improve human comfort conditions?

These questions can either be answered with the help of extensive experiments or by numerical simulations. In this paper a hygrothermal whole building simulation model and its experimental validation and a application under tropical climate conditions will be presented. The model 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 vapour ab- and desorption as a response to the exterior and interior climate conditions, heat sources 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.

2 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 achieved 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. 2003] and is based on the hygrothermal envelope calculation model WUFI® [Künzel 1994].

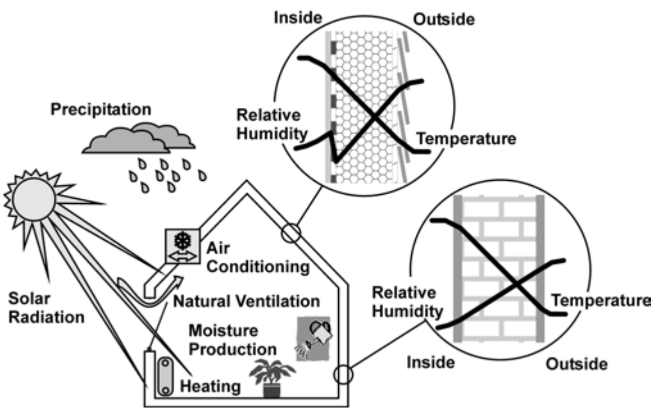

Figure 1: Coupling concept for the simultaneous treatment of the hygrothermal effects of interior heat and moisture loads, exterior climate and transient behaviour of envelope components.

The model for the hygrothermal envelope calculation taking into account vapour diffusion, liquid flow and thermal transport in porous is based on the following equations:

Energy conservation

$$\left(\rho c + \frac{\partial H_w}{\partial \theta}\right) \cdot \frac{\partial \theta}{\partial t} = \nabla \cdot (\lambda \nabla \theta) + h_v \nabla \cdot \left(\delta_p \nabla (\varphi p_{sat})\right) \quad (1)$$

Mass conservation

$$\frac{dw}{d\varphi} \cdot \frac{\partial \varphi}{\partial t} = \nabla \cdot \left(D_w \frac{dw}{d\varphi} \nabla \varphi + \delta_p \nabla (\varphi p_{sat})\right) \quad (2)$$

where
- φ = relative humidity, [-]
- t = time, [s]
- θ = temperature, [K]
- c = specific heat, [J/kgK]
- w = moisture content, [kg/m³]
- p_{sat} = saturation vapour pressure, [Pa]
- λ = thermal conductivity, [W/(mK)]
- H = total enthalpy, [J/m³]
- D_w = liquid diffusivity, [m²/s]
- δ_p = vapour 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 depend on local temperature and humidity conditions. 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 conditions are hardly affected by the building. However, the interior climate conditions depend on several parameters, e.g. exterior climate, HVAC system, occupants' behaviour, humidity buffering of interior walls and furniture.

The indoor air temperature θ_i is linked to the heat fluxes into the room. This means that not only the heat flux through 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 taken into account. The energy balance can be described with the following equation.

$$\rho \cdot c \cdot V \cdot \frac{d\theta_i}{dt} = \sum_j A_j \alpha_j (\theta_j - \theta_i) + \dot{Q}_{Sol} + \dot{Q}_{il} + n \cdot V \cdot \rho \cdot c \cdot (\theta_a - \theta_i) + \dot{Q}_{vent} \quad (3)$$

where:
- ρ = density of the air, [kg/m³]
- α_j = heat transfer coefficients [W/m²K]
- 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]

The humidity 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/m^3

c_i = absolute moisture ratio of the interior air , kg/m^3

$\dot{g}_{w\,j}$ = 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.

3 MODEL VALIDATION

The thermal part of WUFI®+ has already been validated by comparison with well-established building simulation tools [Holm et al. 2003]; however, an important issue is the experimental validation of these models under realistic but well defined boundary conditions. Therefore the following field test was designed for the validation of the humidity related part of the model.

3.1 *Experimental set-up*

The experiments are carried out in a building erected on the IBP test site in the 80s designed for energy investigations published in [Künzel 1984]. Two of the five rooms of this building are suitable for our purpose because they are identical. The ground plan of these rooms and the adjacent spaces is plotted in Figure 2. The rooms have a ground area of 20 m² and a volume of 50 m³. They are well 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 exterior surfaces of the ceiling and partition walls are facing the conditioned space of the test building. The external walls consist of 240 mm thick brick masonry with 100 mm exterior insulation (ETICS also called EIFS). Walls and ceiling of the rooms are coated with 12 mm standard interior plaster. The double-glazed windows are facing south (U-value: 1.1 W/m²K, total solar energy transmittance: 0.57, frame ratio: 30 %). Special care has been taken to make the separate rooms as airtight as possible. Blower-door tests at 50 Pa resulted in air changes below 1 h^{-1}. For the new experiment the walls and ceiling of one room (test room) are rendered moisture inert by sealing them with aluminium foil while the interior surfaces of the other room (reference room) are left as they are. Since the envelope of the test room has no sorption capacity due to the aluminium foil it can be used to determine the moisture buffering effect of furniture and especially installed envelope components. In a second stage wooden lining is applied over the aluminium foiled interior surfaces in order to determine the moisture buffer capacity of wood. The room with unpainted plastered walls represents an example for traditional European residences and serves as reference case.

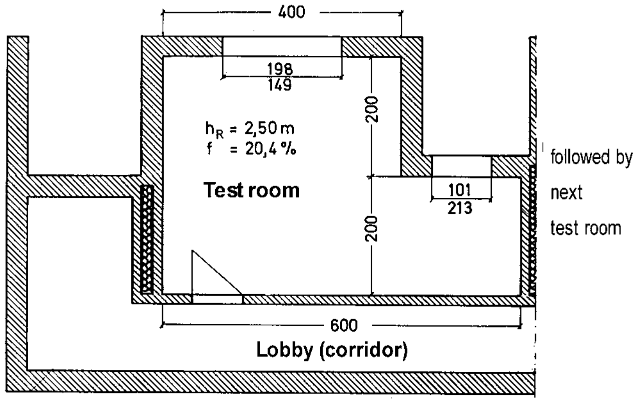

Figure 2: Ground plan of the test room.

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 floor. 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 data acquisition and visualisation tool called IMEDAS (see Figure 3).

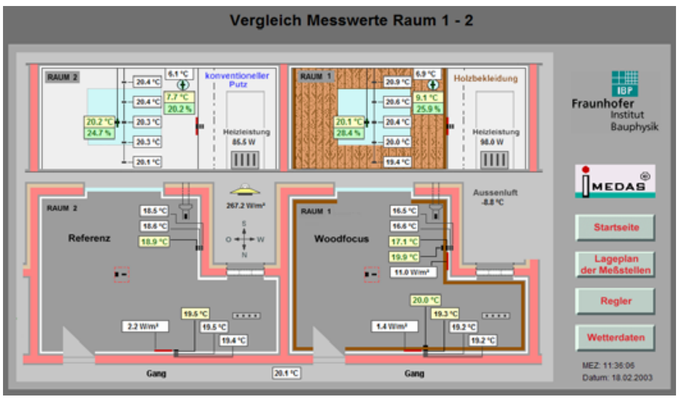

Figure 3: Screen shot of the internet-based visualization tool IMEDAS.

The first tests are done with a constant air change rate (ACH) of 0.5 h^{-1} which is the hygienic minimum rate according to German regulations. The indoor air temperature in the middle of the room is kept above 20 °C. 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. Therefore 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 as demonstrated in Figure 4.

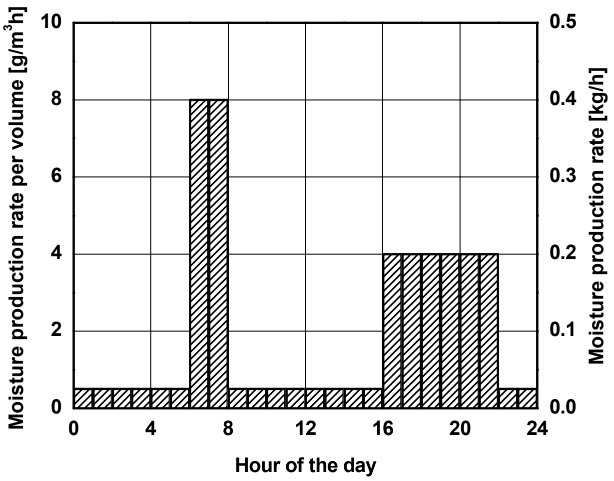

Figure 4: Diurnal moisture production pattern in the test rooms.

3.2 *Numerical Simulation*

The numerical simulations are carried out with the β-version of WUFI®+. The hygrothermal material parameters are taken from the WUFI® 3.3 database. The moisture production and ventilation rate are the same as in the experiment. The outdoor climate data (temperature, RH, solar radiation, etc.) which are continuously recorded at the meteorological station of the IBP are introduced as hourly averages. Surface transfer coefficients are chosen according to Künzel 1994. As initial condition long-term dynamic equilibrium is assumed.

3.3 *Results*

The measured and calculated evolutions of the relative humidity in the empty test room during a day in January are plotted in Figure 5. Since the outdoor climate has been rather constant for some time and the moisture production and ventilation pattern of the room are repeated every day, it is assumed that a dynamic equilibrium has evolved in the room. Therefore the RH of the indoor air at the end of the day is the same as at the beginning. There is a perfect agreement between experiment and numerical simulation. The humidity fluctuations are greatest during the peak load in the morning where the indoor humidity rises from 35% to over 80% which represents an increase of nearly 50% RH.

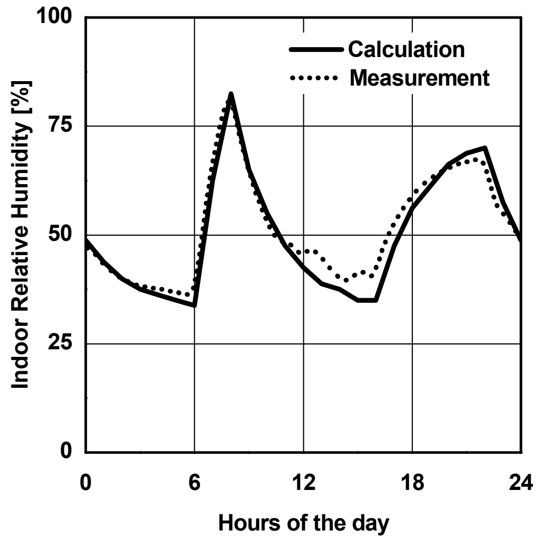

Figure 5: Simulated and measured evolution of the indoor air humidity during a diurnal cycle in the test room coated with aluminium foil.

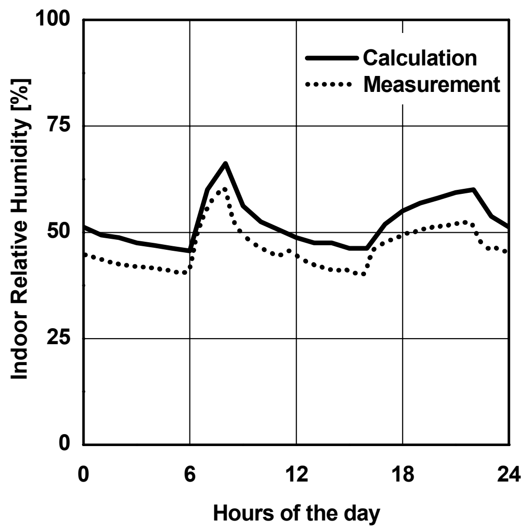

Figure 6: Simulated and measured evolution of the indoor air humidity during a diurnal cycle in the reference room coated with a lime-gypsum interior plaster.

Figure 6 shows the same results for the reference room with the plastered envelope. Again there is a rather good agreement between experiment and calculation, however with a minor offset which is due to a slight difference in the conditions at the beginning of the day. It is assumed that the moisture buffering effect of the envelope retards the dynamic equilibrium in the experiment. This leads to a slightly lower initial RH but does not influence the humidity fluctuations a great deal. The maximum increase in air humidity takes place again in the morning hours but with ca. 20% RH it is considerably lower than in the case of the aluminium foiled test room. This demonstrates the great influence of the vapour absorption capacity of the building envelope.

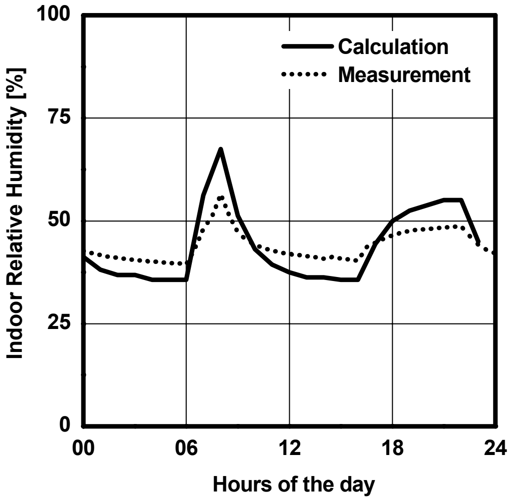

Figure 7: Simulated and measured evolution of the indoor air humidity during a diurnal cycle in the test room when walls and ceiling were covered with wooden panels.

After the initial tests the aluminium foiled test room was lined with wooden panels in order to increase its moisture buffering capacity. Apart from the outdoor climate which was only slightly different all other boundary conditions were left unchanged. The resulting indoor air humidity evolutions are plotted in Figure 7. The measured curve shows very limited humidity fluctuations. The maximum increase in the morning hours is less than 20% which means that the wooden panels have a greater moisture buffering capacity than the unpainted interior plaster. However, this is not captured by the simulated curve which clearly deviates from the measured one. Apparently the hygrothermal properties for wood in the database which were determined by steady state laboratory tests do not represent the transient diffusion and absorption characteristics of the panel surfaces. This effect which has been described by [Hakansson 1998] as non-fickian behaviour must probably be taken into account in order to get a better agreement between simulation and experiment in the case of wood based building envelope materials.

4 MODEL APPLICATION

Since the model seems to work quite well for the rooms examined with and without moisture buffering capacity of the interior plaster, it is applied to investigate the indoor humidity evolution in a building under tropical climate conditions. Let's assume that our test rooms are transferred to Bangkok where they serve as hotel rooms which are occupied during the night from 8°° p.m. to 8°° a.m. and unoccupied the rest of the day. The ventilation system provides constantly 0.5 ACH but the air-conditioning is only working as long as the room is occupied. When the room is unoccupied there is an interior heat and moisture production rate of 100 W res. 0.5 g/m³h (caused by moisture release from plants or furniture). During night-time occupation the interior heat production rises to 500 W and the moisture production to 2.0 g/m³h. The set-points for the intermittently working temperature and humidity controlled air-conditioning system are 25°C and 50% RH. The partition walls to the adjacent rooms are adiabatic while the wall to the corridor and the ceiling face a conditioned space which is kept round the clock at 25°C and 50% RH.

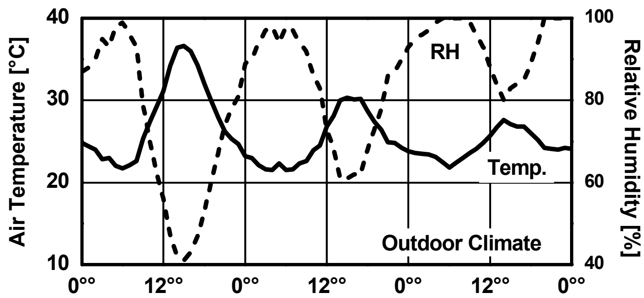

Figure 8: Outdoor air temperature and relative humidity recorded for Bangkok in March (3 day observation period).

The simulation results describing the hygrothermal behaviour of the test rooms with and without moisture buffering capacity are presented for a period of three days in March. The outdoor temperature and humidity conditions for that period are plotted in Figure 8. The evolutions of the indoor air conditions are shown in Figure 9. After shutting off the air-conditioning the indoor temperature rises almost independently of the interior lining of the rooms from the set-point of 25°C to a maximum of 26.7°C during the first day which is also the hottest day of the observed period. When the air-conditioning is turned on again the set temperature is regained within less than one hour.

The evolution of the indoor humidity is, however, greatly affected by the interior lining of the rooms. Due to the more humid outdoor air conditions during the third day of the observed time period the increase in indoor RH is highest in the evening just before the end of the AC shut-off period. While the indoor humidity in the plastered room stays below 75% RH even under the unfavourable conditions of the third day, it clearly exceeds 80% RH in the room with aluminium lining. According to [Sedlbauer 2001] the risk of mould formation increases dramatically when the relative humidity in a room goes beyond 80% several times a week. Therefore a sufficient humidity buffering capacity of the walls and ceiling of a room can help to avoid fungal contamination in a situation where intermittent air-conditioning is employed for energy savings.

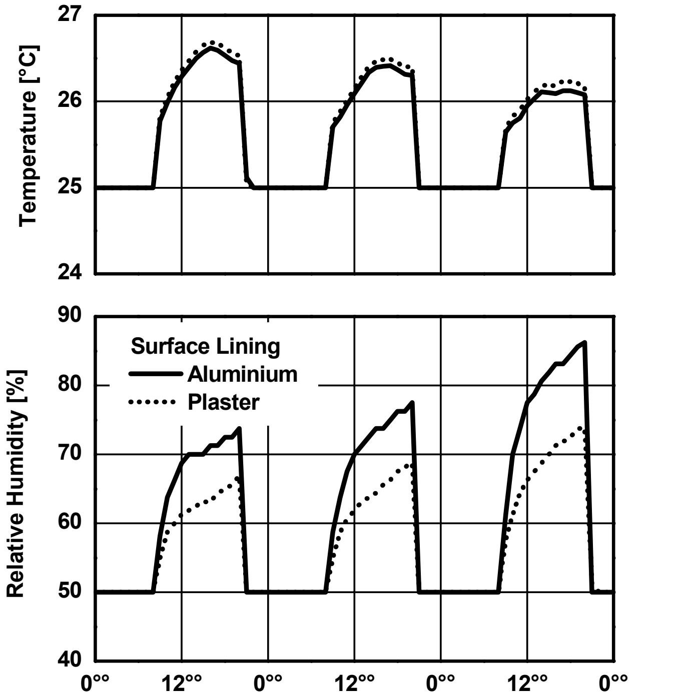

Figure 9: Simulated indoor temperature and relative humidity during the observation period in March (Bangkok climate).

The lower indoor humidity peaks in the plastered room are a result of the vapour sorption of the plaster which is charged with moisture during the AC shut-off period. This additional moisture has to be removed when the AC-system turns back on again. This effect can also be detected looking at the required cooling power of the AC-system in Figure 10. While the sensible heat removal is nearly the same for both rooms, the energy consumption to remove the latent heat from the plastered room is slightly higher because the plaster releases the vapour it has stored during the AC shut-off period

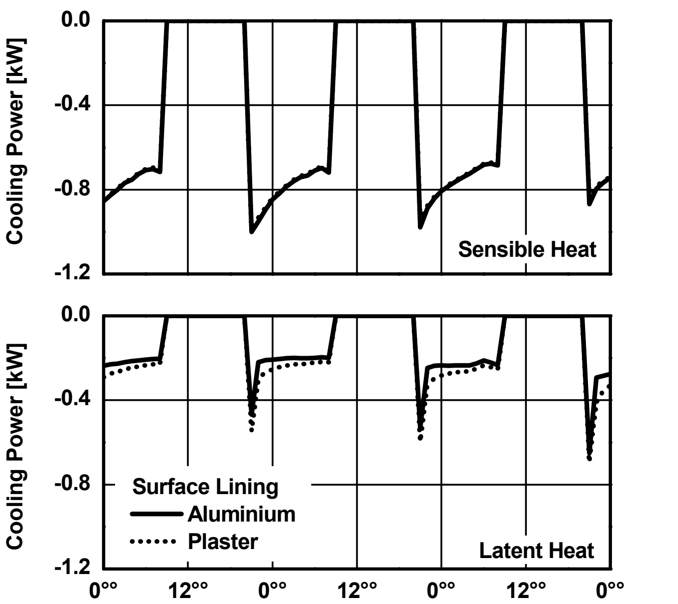

Figure 10: Sensible and latent cooling load to be removed in the different rooms by the AC-system during the observation period.

5 CONCLUSIONS

The hygrothermal behaviour of the building envelope has an important effect on the overall performance of a construction. Therefore, a combined tool for hygrothermal envelope calculations and whole building simulations has been developed and first steps to validate the model have been successfully completed. The results are promising but many more validation examples are necessary in order to gain confidence in the new model and enhance its performance. Since there are some building materials that react differently when exposed to transient instead of steady state conditions more appropriate hygrothermal parameters may have to be determined for hygrothermal building performance calculations.

Models like the one presented here will help to improve energy simulations because latent heat loads and their temporal pattern can be calculated more accurately. At the same time the determination of indoor air and surface conditions in a building becomes more reliable. This is very important to assess indoor air comfort and hygiene. Post processing models for the determination of mould growth [Sedlbauer 2001] or corrosion risks rely on accurate results of the transient temperature and humidity conditions. The same holds for the design of HVAC systems in heritage buildings or museums [Harriman et al. 2001] where the humidity buffering capacity of the envelope and furniture helps to control temperature and humidity fluctuations.

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