ON MODELLING MOISTURE BUFFERING WHEN EVALUATING HUMIDITY CONTROLLED HVAC SYSTEMS

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ABSTRACT

As most building energy simulation programs focus on the thermal response of the building, the relative humidity of the indoor air is often calculated in a simplified way. One of the main shortcomings is the isothermal calculation, which may have a strong influence the predicted relative humidity. In this paper the use of a simplified effective moisture penetration depth (EMPD) model is compared with a coupled TRNSYS-HAM-model. First, an estimation of the load for humidification and dehumidification is made. Results showed that the EMPD-model underestimates the humidification load because the model disregards non-isothermal effects. Secondly, calculations showed that the indoor and surface relative humidity of an office room with a gypsum cooled ceiling are overestimated using the EMPD-model. Furthermore, due to not including non-isothermal effects the peak load for dehumidifying the ventilation air may be underestimated using an EMPD-model.

INTRODUCTION

The moisture balance of a room is affected by ventilation, infiltration, moisture gains and adsorption and desorption of moisture at porous surfaces. Hygroscopic materials such as wood and textiles are able to damp relative humidity variations and therefore create a more stable indoor climate. Apart from other parameters such as air temperature and air velocity, indoor comfort and perceived air quality are also affected by the relative humidity in the building. Moreover, the presence of possible condensation and mould growth, and the deterioration of building materials are determined by the indoor humidity.

However, most building energy simulation (BES) programs e.g. TRNSYS, Energy+ focus on the thermal response of the building, while the relative humidity is calculated in a simplified way [SEL 2004]. Typically an effective capacitance (EC-) model or a effective moisture penetration depth (EMPD-) model is used to account for moisture buffering in porous materials. These models can be used to give a first estimation of the moisture buffering capacity of a room. In contrast HAM-models (Heat Air Moisture) describe combined heat and moisture transfer in porous materials and make a more accurate prediction of the indoor relative humidity possible.

In the frame of the recent international research project ‘Annex41: Whole-Building Heat, Air and Moisture response’ attention was drawn to a whole building hygrothermal modelling approach and efforts were undertaken to couple BES-codes with HAM-models. Several researchers focused on the interaction between HVAC-systems and the indoor moisture balance, which may be significant in buildings with high hygroscopic moisture contents e.g. museums and libraries [IEA 2008]. The importance of including moisture buffering in sizing and evaluating humidity-controlled HVAC-systems was already stated by several authors: Woloszyn et.al. [2008] included moisture buffering to evaluate humidity-controlled ventilation and Maalouf et.al. [2005] evaluated a desiccant cooling system including hygrothermal interactions with the building envelope. Catalina et.al. [2006] described the importance of including moisture buffering when evaluating the performance of cooled ceilings. In this case moisture buffering was taken into account using the EMPD-model in TRNSYS. A dewpoint temperature sensor at the ceiling surface controlled the allowable water temperature in the tubes to prevent surface condensation. Including moisture buffering resulted in lower allowable water temperatures and thus a higher achievable cooling power. ISSO [1998] denotes that such systems are usually sized without taking into account moisture buffering.

This paper focuses on the relation of model used to describe moisture buffering and the predicted performance of a humidity-controlled HVAC system. A comparison is made between the EMPD-model available in the TRNSYS-code and a HAM-model which was recently coupled with TRNSYS. First the impact of the chosen model to predict humidification and dehumidification loads of a building is studied. Secondly, the influence on the evaluation of gypsum cooled ceilings is looked at.

MODELLING INDOOR HUMIDITY

Governing equations

The non-steady state moisture balance of a room can be written in terms of water vapour pressure as:

$$\begin{aligned} & G_p + G_{sys} + \frac{nV}{R_v T_i}\left(p_e - p_i\right) \\ & = \frac{V}{R_v T_i}\frac{dp_i}{dt} + \sum_j A_j \beta_j \left(p_i - p_{s,j}\right) \end{aligned} \tag{1}$$

The left handside contains the moisture sources (G_p moisture production by e.g. humans, G_{sys} moisture introduced by the HVAC-system and moisture introduced by ventilation), the right handside shows the storage in the room air and the convective vapour transfer from the room to the hygroscopic surfaces. The mass balance equation for 1-D moisture transfer by vapour diffusion in a hygropscopic wall can be written as:

$$\begin{aligned} & \frac{\partial w}{\partial t} = \frac{\partial w}{\partial \phi}\frac{\partial \phi}{\partial t} = \rho\xi(\phi)\frac{\partial \phi}{\partial t} \\ & = \frac{\partial}{\partial x}\left[\delta(\phi)\frac{\partial}{\partial x}\left(\phi.p_{sat}(T)\right)\right] \end{aligned} \tag{2}$$

Finally the boundary condition at the material surface can be written as (coupling between Eq.(1) and (2)):

$$\beta_i\left(p_i - p_s\right) = -\delta(\phi).\frac{\partial p}{\partial x}\bigg|_s \tag{3}$$

Simplified approach: EMPD-model

Eq. (2) and (3) are now solved assuming that only a thin layer at the indoor surface exchanges moisture with the indoor air. The thin buffering layer has a uniform water vapour pressure and its depth Δ is related to the period t of the moisture variation cycle. This moisture penetration depth Δ can be calculated using Eq.(4), thus reducing Eq. (2) and (3) to Eq. (5). The subscript ‘b’ denotes the node in the middle of the penetration depth.

$$\Delta = \sqrt{\frac{\delta.p_{sat}(\theta).t}{\rho\xi.\pi}} \tag{4}$$

$$\rho\xi(\phi_b)\Delta\frac{d}{dt}\left(\frac{p_b}{p_{sat}(\theta_b)}\right) = \frac{p_i - p_b}{\dfrac{1}{\beta_i} + \dfrac{\Delta}{2\delta(\phi_b)}} \tag{5}$$

In TRNSYS the buffering layer is further divided into a surface layer and a deep layer to account for both short-term and long-term exchanges [SEL2004]. Using the EMPD-model in TRNSYS implies following simplifications:

- Isothermal calculation
- Constant material properties: water vapour permeability $\delta(\phi_b)$ and specific moisture capacity $\rho\xi(\phi_b)$. Generally the properties are calculated at $\phi = 50\%$.
- Water vapour diffusion through construction is not taken into account

Another drawback of this model is the difficulty to introduce various hygroscopic materials, which requires the use of area-weighted material properties. In the next sections the parameters of the EMPD-model were chosen in such a way that the the same results were obtained as with the HAM-model for a simulation with a stationary outdoor climate.

TRNSYS – HAM modelling

The HAM-model used in this paper describes one-dimensional transient heat and moisture transfer through a porous multilayer wall, and was coupled with TRNSYS [Steeman 2008]. As moisture buffering occurs mainly by vapour diffusion, liquid flow is not considered in the model. The heat and mass balance equation (Eq.2and6) are iteratively solved using a control volume method and an implicit time discretisation scheme. The material properties depend on the moisture content of the material and are updated every timestep. Sorption hysteresis is not taken into account.

$$\begin{aligned} & \frac{\partial h}{\partial t} = \rho c_p \frac{\partial T}{\partial t} \\ & = \frac{\partial}{\partial x}\left(\lambda(\phi).\frac{\partial T}{\partial x}\right) + h_v \frac{\partial}{\partial x}\left[\delta(\phi)\frac{\partial}{\partial x}\left(\phi.p_{sat}(T)\right)\right] \end{aligned} \tag{6}$$

The modular structure of TRNSYS allows to implement the HAM-model as a new module. In this way it is possible to account for the response of a multizone building on moisture buffering effects. The heat and moisture balance of a zone are calculated in the TRNSYS multizone model. The relative humidity ϕ_z and temperature θ_z of a zone, as well as the surface temperatures at both sides of the wall (θ_{s1},θ_{s2}) are used as an input in the HAM-model, which in turn returns a vapour flux g_v(kg/m².s) to the multizone model (figure1). Both models are called iteratively until convergence is reached. The coupled TRNSYS-HAM model was verified against two analytical cases in [Steeman 2008] and showed very good agreement.

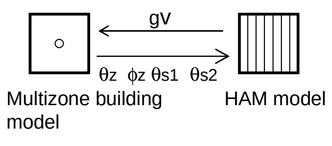

Figure1: TRNSYS – HAM coupling

Contrary to the EMPD-model, TRNSYS allows to introduce multiple HAM-models to easily account for the moisture buffering effect due to various hygroscopic materials.

APPLICATIONS

Estimating humidification and dehumidification loads

In order to keep the relative humidity to its target value, humidification or dehumidification may be desired in some buildings. For example in museums or libraries a stable relative humidity is essential in order to prevent the objects or books from e.g. mechanical damage. According to ASHRAE's conservation classes, the relative humidity is preferably situated between 40% and 60%. Generally, loads for humidification and dehumidification systems are predicted using a steady-state calculation. Nevertheless,without taking into account moisture buffering in hygroscopic surfaces these loads may be overestimated.

In the current analysis the BESTEST-building from Common Exercise01B was used to calculate the humidification and dehumidification load [IEA 2008]. The building has a volume of 129.6m³ and is ventilated with outdoor air (constant 0.5ach). Moisture is generated at 0.5kg/h every day during 09-17h. Initial temperature and relative humidity are 20°C and 50%. The indoor heating and cooling setpoint are respectively 20°C and 25°C, in between the indoor temperature is free floating. Water vapour is adsorbed and released by 15cm thick exterior walls (171.6m² aerated concrete). Moisture properties are taken from [IEA 1991]:

-Thermal conductivity $\lambda = 0.176 + 0.000801 \cdot w$

-Water vapour resistance

$$\mu = \left(0.116 + 0.00628 \exp(4.19 \cdot \phi)\right)^{-1}$$

-Moisture content

$$w = 300\left(1 - \left(\ln\phi \big/ 0.0011\right)\right)^{-1/1.99}$$

The loads for humidification and dehumidification were simulated seperately using a set point of ϕ=40% and ϕ=60% respectively. Simulations were run for one year, using a timestep of 0.125h. Uccle (Belgium) weather data were used.

The HAM-model describes the porous material of the building using one wall having a buffering surface of 171.6m². The surface temperatures of the west-oriented wall are used as an input to the model. The model uses the moisture-dependent material properties given above. The porous wall was descretized in 30 controlvolumes, ranging from 3mm at the edges to 7.7mm in the middle of the wall. The EMPD-model uses constant material properties at ϕ=50%, resulting in a moisture capacity ρξ=17kg/m³ and a vapour diffusion resistance μ=5.98. The surface and deep penetration depth were respectively 9.6mm and 3.8cm.

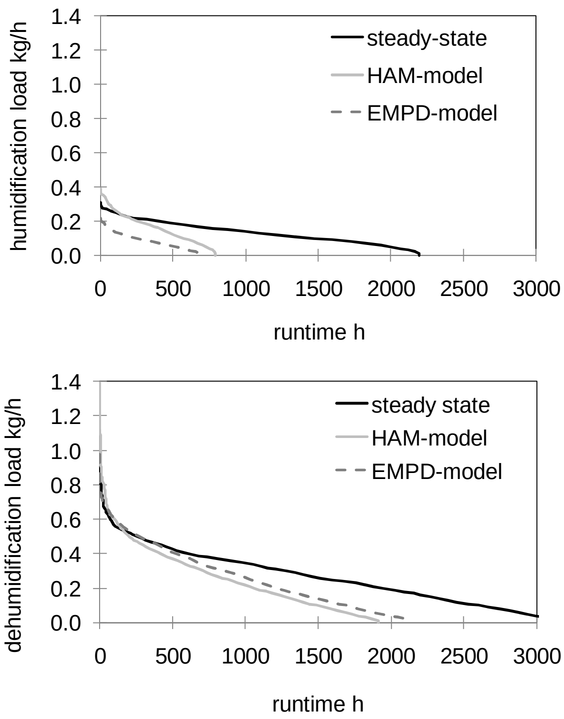

Figure2: Predicted humidification (setpoint 40%) and dehumidification (setpoint 60%) load profiles

Table1: Predicted humidification and dehumidification loads (steady-state, EMPD, HAM)

	Humidification	Dehumidification
Steady - state		
Average ϕ [%]	59.3	48.2
Total load [kg]	275.1	808.2
Peak load [kg/h]	0.29	1.11
Runtime [h]	2196	3171
EMPD – model		
Average ϕ [%]	57.9	51.6
Total load [kg]	53.6	554.1
Peak load [kg/h]	0.20	0.95
Runtime [h]	672	2132
HAM – model		
Average ϕ [%]	55.4	50.9
Total load [kg]	120.6	482.8
Peak load [kg/h]	0.37	1.37
Runtime [h]	788	1911
HAM – model insulated exterior walls (5cm MW)		
Average ϕ [%]	54.7	50.9
Total load [kg]	100.8	413.0
Peak load [kg/h]	0.30	1.13
Runtime [h]	773	1852

Figure 2 shows the predicted yearly humidification and dehumidification load profiles of three models. The humidification and dehumidification systems are modelled as ideal systems with the proper capacity to meet the setpoints at all times. It proves that without including moisture buffering (steady-state), the total yearly loads for humidification and dehumidification are overestimated. The average relative humidity predicted by the HAM-model is lower than calculated with the EMPD-model (table1). This results in a higher estimated total load, peak load and runtime for humidifiying and a lower load for dehumidification. This can be explained by water vapour diffusion through the vapour open aerated concrete walls and by the enlarged moisture buffering effect in the HAM-model. The latter is driven by the temperature gradient over the exterior walls. Both effects are not taken into account in the EMPD-model.

The HAM-model estimates the highest peak loads because it takes into account the temperature gradient over the wall. If for example the temperature at the indoor surface increases, at first the relative humidity is in equilibrium with the indoor air and remains unchanged while the vapour pressure alters. As a result a net vapour flux is created towards the room resulting in a peak load for dehumidification. Thus this instant desorption or adsorption of the wall results in higher peak loads. If we assume that the exterior walls are insulated with 5cm of mineral wool at the outer side the total and peak load for both humidification and dehumidification and the runtime are lower due to the smaller temperature gradient over the exterior walls (table1). In these calculations the mineral wool was assumed to have negligable vapour resistance and moisture capacity.

Furthermore table1 shows that the estimated load for dehumidification is higher than for humidification. The loads for dehumidification predicted by the HAM-model and the EMPD-model agree better than the predicted humidification loads, the EMPD-model however overestimates the total load and runtime.

In order to evaluate the differences in the loads predicted by the EMPD-model and the HAM-model more in detail, variations to the original HAM-model are made to evaluate the sensitivity of the model to the different simplifications in the EMPD-model:

- Isothermal model: a constant wall temperature of 20°C is used in the HAM-model
- Outside wall vapour tight: vapour diffusion through the construction is thus excluded.
- Constant material properties (at ϕ=50%): specific moisture capacity $\rho\xi$=17kg/m³ and water vapour diffusion resistance μ=5.98.

Table2 shows that an isothermal calculation has the largest influence on the predicted load for humidification and dehumidification. Performing an isothermal simulation of the exterior wall has a large impact on the predicted load. In this case the additional buffer effect due to the temperature gradient in the wall is neglected thus a lower total and peak load for both humidification and dehumidification are predicted. When assuming a vapour tight boundary at the outer side of the construction vapour diffusion through the wall is neglected. Although therefore we would have expected a smaller humidification load a higher load both for humidification and dehumidification is noted in the simulation results. When constant material properties are assumed the expected load for humidification decreases because moisture capacity of the walls is underestimated (average relative humidity>50%). On the other hand the dehumidification load is also lower because the the buffering effect is overestimated (relative humidity generally <50%).

Table2: Predicted humidification and dehumidification loads (variations on HAM-model)

	Humidification	Dehumidification
HAM - model isothermal calculation		
Average ϕ [%]	54.7	50.9
Total load [kg]	101.7	395.3
Peak load [kg/h]	0.28	0.99
Runtime [h]	824	2018
HAM – model vapourtight assumption		
Average ϕ [%]	56.2	50.7
Total load [kg]	130.5	496.1
Peak load [kg/h]	0.38	1.43
Runtime [h]	820	1939
HAM – model constant material properties		
Average ϕ [%]	55.3	50.8
Total load [kg]	116.5	458.9
Peak load [kg/h]	0.37	1.34
Runtime [h]	772	1850

Evaluating gypsum cooled ceiling

Cooled ceilings may be an interesting cooling technique as well for new or retrofit buildings in which cooling is realized by both radiation (mainly) and convection at the ceiling surface. The cooling power depends on the temperature difference between room and ceiling surface. Generally metal cooled ceilings are used in most applications, however also gypsum cooled ceilings can be found. Disadvantages of gypsum cooled ceilings may be their reduced cooling power due to the insulating gypsum layer. At the other hand the porous gypsum layer is able to adsorb and desorb water vapour and the application of gypsum surfaces may therefore lead to a more stable indoor climate [Simonson 2002].

However, care should be taken when applying both metal and gypsum cooled ceilings in order to prevent condensation on the cold ceiling surface. Therefore the ventilation air is generally dehumidified in the air handling unit. Furthermore the risk of condensation and mould growth within the gypsum layer should be prevented as well.

Model description

The hygroscopic cooled ceiling system consists of 15mm gypsum, covered by an aluminium foil and 24mm of EPS insulation at the back side. A circuit of watertubes is placed in the gypsum layer. The inlet and outlet of the circuit is connected with a main water tube. The water tubes have an outer diameter of 6mm. The inlet watertemperature can range from 8°C to 18°C.

The cooled ceiling is used in an office space (45m³) having a floor area of 18m² (5.0m x 3.6m) with a height of 2.5m. All walls are internal walls, except for the south-oriented glass façade (U_{window}= 0.86W/m²K, solar admittance factor g=0.6). Sunshading is present, resulting in a total solar admittance factor of 0.42. Construction details are given in table3. Occupancy in the office is from 07-19h. Internal heat and moisture gains are due to people (10W/m² and 0.10kg/h), devices (8W/m²) and lights (10W/m²).The office is ventilated with outdoor air (1.44ach, 70m³/h) from 06h to 20h. If the outdoor air is warmer than 26°C the ventilation air is precooled to 26°C, the air is preheated to 15°C if the outdoor temperature is lower. A sunshading is used if the irradiance on the façade exceeds 200W/m² (hysteresis 150W/m²). The cooled ceiling is in operation during the occupancy hours if the indoor operative temperature exceeds 24°C and shuts down if the operative temperature is lower than 21°C (to prevent the system of switching on/off due to high power). The system has a minimum operation time of 30minutes.

Table 3: Construction details

	d [m]	λ[W/m²K]	ρ [kg/m³]
(Half) internal wall (d 0.06m - U 0.61W/m²K)			
Plaster	0.01	0.22	800
Mineral wool	0.05	0.035	20
Floor - Ceiling (d 0.245m – U 0.71W/m²K)			
Ceramic	0.025	0.8	1700
Tile bedding	0.05	1.4	2100
Reinforced concrete	0.13	1.9	2300
EPS	0.04	0.04	30
Gypsum	0.015	0.16	800

Apart from moisture buffering in the cooled ceiling (18m²) no other hygroscopic materials were present This means that moisture buffering in internal walls or in furniture is not taken into account.

Moisture buffering in the gypsum cooled ceiling is modelled both with the EMPD and the HAM-model. The cooled ceiling was regarded as a 1D-problem: assuming a water temperature of 10°C in the tubes, the average temperature at the centre of the tubes (θ_g) was preliminary calculated using a 2D-model and was 12.5°C. This value was used as an input for the HAM-model. The ceiling surface temperature was calculated by building model in TRNSYS. The back side of the gypsum layer had a vapour tight boundary. In figure 4 the HAM-model is presented schematically. The gypsum layer was discretized into 20 controlvolumes, having a thickness ranging from 0.5mm at the edges to 1.1mm in the middle of the gypsum layer. Initial conditions for the gypsum were 20°C and ϕ 50%. Material properties of gypsum were [IEA 1991]:

-Thermal conductivity $\lambda = 0.263 + 0.00099 \cdot w$

-Water vapour diffusion resistance

$$\mu = \left(0.155 + 0.00076 \exp(4.64 \cdot \phi)\right)^{-1}$$

-Moisture content

$$w = 310\left(1 - \left(\ln\phi / 0.032\right)\right)^{-1/1.58}$$

The EMPD-model calculates isothermally with following constant material properties (at ϕ=50%): moisture capacity ρξ=75.6kg/m³ and vapour resistance μ=6.1. The penetration depth of the surface and deep layer were 9.4mm and 3.8cm.

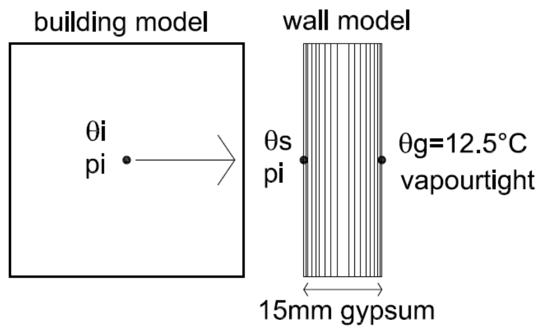

Figure 4: Scheme of the HAM-model and boundary conditions used to model the cooled ceiling

Simulations in TRNSYS are performed using a weatherfile for Uccle (Belgium) for the summer season (01/07 to 30/09). The simulation timestep was 5 minutes. Solar radiation is taken into account.

Evaluation criteria

Criteria for evaluation of the cooled ceiling are:

- Avoidance surface condensation
- Avoidance of mould initiation

In summer humid outdoor air may condensate against the cold ceiling if the air temperature is lower than the dewpoint temperature of the ceiling surface. Condensation may as well occur at the water tube surface. Secondly mould growth is initiated if the relative humidity at the surface or in the gypsum exceeds 80% (IEA 1991).

In order to evaluate the performance of cooled ceilings in a correct way it is necessary to include moisture buffering. When including moisture buffering the ventilation dehumidification load is expected to be smaller and the indoor and surface relative humidity to be lower. Also, the buffering effect may be underestimated using a simplified model. Due to the non-isothermal origin of this problem two phenomena influence the driving forces for water vapour diffusion: water vapour production due to occupancy and temperature gradients on the one hand between the indoor air and the ceiling suface and secondly in the gypsum layer due to the cooled ceiling. These effects are both included using a HAM-model.

Results

Simulations were run for the entire summer period. Using above described control strategy the system was in operation during 385h of the 1104 occupancy hours. The indoor operative temperature ranged from 18.8°C to 24°C if the system was in operation and from 18.9°C to 27.9°C in case there was no cooled ceiling present.

In figure 5 temperatures are presented for three summer days (17-19/08.). The outside temperature was between 13.1°C and 28.4°C, on average it was 22.2°C. The cooled ceiling system was usually in operation during occupancy. In that case the surface temperture ranged from 16.7°C to 19.4°C, with an average of 17.9°C. The periods in which the cooled ceiling was in operation are depicted in figure 5.

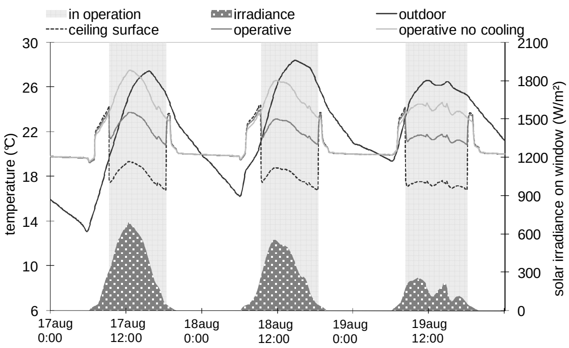

Figure 5: Indoor, outdoor and surface temperature (17/08-19/08)

Next, the results obtained by using respectively an EMPD-model and a HAM-model to account for moisture buffering, were evaluated. The results are compared with a calculation in which no moisture buffering is taken into account. This may correspond to a metal cooled ceiling, which lacks porous material. Figure 6 shows the indoor vapour pressure and the periods during which the cooled ceiling system was in operation. To fully see the influence of the different models, dehumidification of the ventilation air was not taken into account.

Not including moisture buffering shows larger vapour pressure variations than using the EMPD-model. On the other hand, using the HAM-model shows a vapour pressure decrease when the cooled ceiling is in operation: due to the temperature gradient between the indoor air and the ceiling surface, the moisture buffering effect is larger than expected with an isothermal model. When the cooled ceiling starts to operate, the ceiling surface temperature decreases, at first keeping its relative humidity stable thus decreasing the water vapour pressure. Because cooling demand generally coincides with occupancy instantly water vapour is adsorped by the gypsum layer, showing the decreased water vapour pressure in figure6. Once the cooled ceiling is initiated, due to the internal and solar gains the ceiling surface temperature increases, resulting in a smaller temperature gradient with the office air. In turn the adsorption of water vapour slows down, as is seen by the slightly increasing water vapour pressure on figure 6. If the cooled ceiling shuts down, the surface temperature increases, at first keeping its relative humidity stable and thus increasing its vapour pressure. Instantly moisture is released from the gypsum surface resulting in the higher room vapour pressure shown in figure 6. The same happens in the morning before the cooled ceiling is in operation: due to solar irradiance the ceiling temperature increases above the room temperature resulting in a vapour desorption and thus a peak in the room vapour pressure.

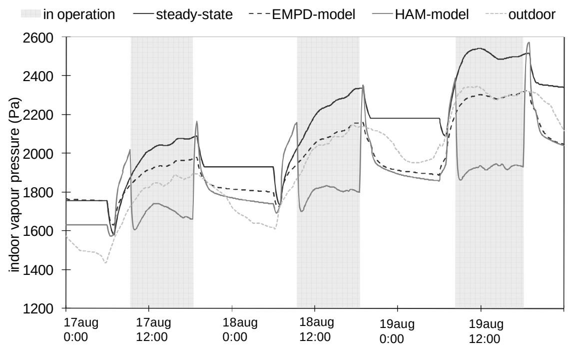

Figure 6: Indoor vapour pressure (17/08-19/08) – no dehumidification of the ventilation air.

Figure 7 shows that without including dehumidification to the ventilation air, the surface relative humidity is overestimated when using the EMPD-model or using a steady-state calcualtion. It must be noted that because the inertia of the cooled ceiling is not included in the simplified 1D model used in the simulations, in reality the changes in surface temperature gradients will be smoother and thus the relative humidity peaks due to starting or shutting down the cooled ceiling will be smaller.

Figure 8 (right) presents the temperature, relative humidity and vapour pressure in the gypsum layer, calculated with the HAM-model. The results are compared with a HAM-model in which non-isothermal effects are not taken into account (left): the gypsum layer had a constant temperature equal to the average surface temperature (17°C). Initial conditions of the gypsum layer are again 20°C and ϕ=50%.

Taking into account the temperature gradient over the gypsum layer the temperature varies from about 17-18°C at the ceiling surface to 12.5°C near the water tubes. Due to a temperature gradient in the gypsum layer, water vapour is diffused deeper into the material. Therefore the relative humidity at the surface is lower when including temperature gradients. Not including non-isothermal effects both surface tempeatures are 17°C. The temperature in the gypsum slightly increases due to latent heat being released when water vapour is adsorbed by the gypsum. The relative humidity deeper in the gypsum layer is not influenced by moisture buffering.

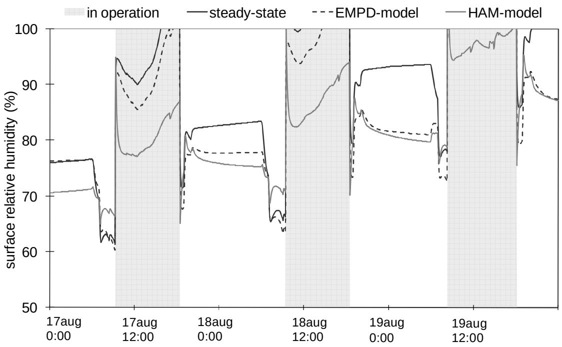

Figure 7: Ceiling surface relative humidity (17/08-19/08) – no dehumidification of the ventilation air

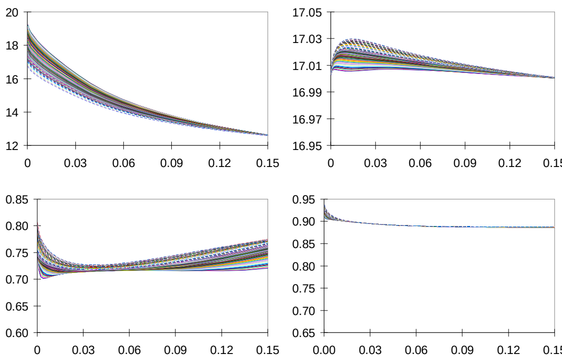

Figure8: Temperature (up) and relative humidity (under) in the gypsum cooled ceiling on 17/08 (no dehumidification – cooled ceiling in operation) (Left: non-isothermal – Right: isothermal)

Next the necessary dehumidification load was calculated using the same models as in the evaluation above. The relative humidity setpoint was determined to avoid surface condensation both at the ceiling surface and against the watertubes and to avoid mould growth. The maximum allowable indoor vapour pressure would thus be the minimum of following values:

- at θ_{surf} ~ 17°C ; ϕ_{max} = 80% (mould)
- at θ_{water} ~ 10°C ; ϕ_{max} = 100% (condensation)

The maximum allowable indoor vapour pressure was set to 1200Pa and the corresponding relative humidity was used as dehumidification setpoint.

Table 4 shows the total load and peak load for dehumidification calculated for the whole summer season (01/07-30/09). Not including the non-isothermal buffering effects underestimates the peak load by about 50%. This is because of the peaks in relative humidity when the cooled ceiling starts or stops, leading to an additional desorption or adsorption effect. The total dehumidification load shows to be slightly higher when using a HAM-model.

Table4: Total (kg) and peak (kg/h) dehumidification load calculated with different models

Applied model	Steady-state	EMPD	HAM
Total load (kg)	302	294	312
Peak load (kg/h)	1.09	1.01	1.47

Figure 9 shows the moisture content of the gypsum layer during the summer period (01July-30Sept.) with and without dehumidification of the supply ventilation air calculated with the HAM-model. The initial moisture content of the gypsum was 0.65kg/m² (at 20°C and ϕ=50%), the saturation moisture content was 4.65kg/m² of ceiling. Without dehumidification the maximum moisture content increased up to 1.53kg/m², with dehumidification the moisture content was more stable and varied around the initial moisture content.

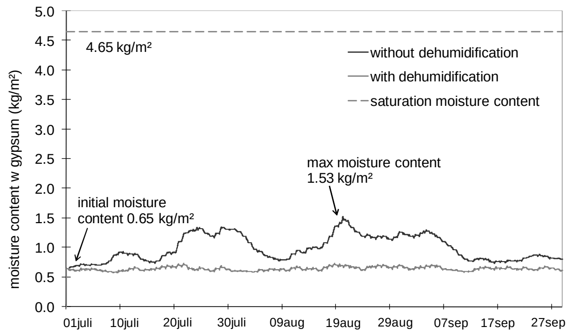

Figure 9: Moisture content of the gypsum layer during summer calculated with the HAM-model

DISCUSSION

The present study confirms that moisture adsorption and desorption at porous surfaces has an important influence on the room moisture balance. Including a whole-building hygrothermal approach is essential when sizing or evaluating humidity controlled HVAC-systems. Simplified isothermal models (e.g. EMPD-models) are often used stating that in insulated buildings the model assumptions are correct because the thin buffering layer has a constant temperature. However, in the studied applications non-isothermal effects showed to have an important influence on moisture buffering. It is important to understand the nature of the studied problem in order to choose a well-suited model to describe moisture buffering effects. Furthermore users should be aware of the limitations of simplified models available in BES-codes. Temperature gradients in walls may be caused by temperature differences between rooms, in poorly insulated walls or due to sudden changes in climatisation control system, solar irradiance etc. Neglecting them may lead to misjudging or misevaluating humidity-controlled HVAC-systems.

CONCLUSION

In this paper a coupled TRNSYS-HAM-model was compared to a simplified EMPD-model typically available in building energy simulation programs. Two applications were considered in which the simplifications of the applied model may be of importance First the predicted yearly loads for humidification and dehumidification were compared for the BESTEST building. Results showed that the EMPD-model underestimates the predicted humidification load because the additional moisture buffering effect due to temperature gradients in the walls is neglected in the simplified model. Secondly a gypsum cooled ceiling was analyzed. Calculations proved that the indoor and surface relative humidity of an office room with a gypsum cooled ceiling are overestimated using the EMPD-model. Furthermore, due to neglecting non-isothermal effects the peak load for dehumidification of the ventilation air may be underestimated using an EMPD-model.

NOMENCLATURE

A	surface [m²]
c_p	specific heat [J/kg.K]
g_v	water vapour flux [kg/m².s]
G	mass flow [kg/h]
h	enthalpy [J/kg]
h_v	latent heat of evaporation [2.5 10^6 J/kg]
n	air change rate [1/h]
$p_{(sat)}$	(saturation) vapour pressure [Pa]
R_v	gas constant for water vapour [J/kg.K]
t	period of cyclic variation [s]
T,θ	temperature [K,°C]
V	volume [m³]
w	moisture content [kg/m³]
β	mass transfer coefficient [kg/Pa.s.m²]
δ	vapour permeability [kg/Pa.s.m]
Δ	effective moisture penetration depth [m]
ϕ	relative humidity [-]
λ	thermal conductivity [W/m.K]
ρ	material density [kg/m³]
ρξ	specific moisture capacity [kg/m³]
Subscripts	
e, i	exterior, interior
b	middle of penetration depth
s, w	surface, water

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