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PREDICTION OF MOLD RISK IN CAVITY WALLS COMBINING A COUPLED CFD/HAM-MODEL AND A 2D HYGROTHERMAL MODEL: THE INFLUENCE OF THE OUTER CAVITY LAYER ON THE INNER CAVITY LAYER

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ABSTRACT

Preventing mould risk in buildings is important to ensure a healthy environment for the people and to avoid material damage. A reliable prediction is especially important for ventilated cavity walls made of a moisture sensitive material such as wood. In this paper the influence of the outer cavity layer on the inner cavity layer has been analyzed. The cavity wall consists of a timber frame on the inside and a brick veneer on the outside separated by an air layer. For this hygrothermal evaluation of air cavities, coupled CFD/HAM-software and a commercial hygrothermal software package WUFI-2D® are used. First the coupled CFD/HAM-software is used to examine the heat and mass transfer coefficients at the surfaces between the air and the material layer and the applicability of the heat/mass-analogy. Afterwards, the effect of long-wave radiation in the cavity will be simulated with the coupled CFD/HAM-model. Finally the model developed in WUFI to simulate a ventilated cavity wall and the influence of different materials for the outer layer will be examined combining the coupled CFD/HAM-model and WUFI-2D.

INTRODUCTION

To predict the risk of mould in ventilated air cavities, an accurate simulation model is important. Instead of experiments, in the last decades the use of commercial CFD-software increased in the construction industry. It is able to simulate airflows and heat transfer in building constructions. In [1] 3-dimensional CFD-simulations are used to analyse the airflow in small, ventilated cavities. The velocity profiles for different cavity configurations, wind velocities and wind directions were analysed. In [2] Rodrigues simulates the effect of natural and forced convection in cavities on the heat transport. The result is a decline of the heat losses from inside to outside in the summer and an incline in winter. Next to Rodrigues also Gustavsen, Thue and Gan simulated the effect of natural convection on the heat transport in cavity walls [3,4]. A minority of these articles implement the effect of long-wave radiation in the cavity.

Most of the commercial CFD-programs do not implement the transfer of vapour through the air and in porous materials. In [5] a coupled CFD/HAM-model is developed to predict the moisture damage in constructions. This model uses the commercial CFD program Fluent® to solve the Navier-Stokes equations in the air. An extra set of equations was added to the model to solve the heat and moisture transport in hygroscopic porous materials as well. This model only uses the vapour transport equations and not the transport equations for liquid. A more detailed elaboration of the implemented set of equations is found in [5]. Because of the long calculation time of such simulation models, simplified HAM-models are often used in the construction industry to predict mould risk. An overview of some of these HAM models is given in [6]. These models use some simplifications to reduce the calculation time. Künzel [7] added a model to WUFI-2D® to simulate a ventilated air cavity. An extra heat and moisture source was added to the air cavity depending on the air change rate. A good agreement with experiments was found.

The coupled CFD/HAM-model can give a better understanding of the flow characteristics in a cavity and can analyse the accuracy of the added model in WUFI-2D® to simulate a ventilated air cavity.

NOMENCLATURE

ACR	[1/h]	Air Change Rate
CFD		Computional Fluid Dynamics
C	[J/kgK]	Heat capacity
g	[kg/(s.m^2)]	Mass flux
h	[J/kg]	Enthalpy

HAM		Heat Air and Moisture
OSB		Oriented Strand Board
p	[Pa]	Pressure
K	[s]	Moisture permeability
q	[W/m^2]	Heat flux
R	[K/W]	Thermal resistance
RH	[%]	Relative Humidity
v	[m/s]	Velocity
w	[kg/m^3]	Moisture content
x	[m]	Thickness
Y	[-]	Mass fraction

Special characters

α	[W/m^{2}K]	Heat transfer coefficient
β	[s/m]	Mass transfer coefficient
λ	[W/mK]	Thermal conductivity
μ	[-]	Diffusion resistance factor
ϕ	[-]	Porosity
ρ	[kg/m^3]	Density
Θ	[°C]	Temperature

Subscripts

cav	Cavity
e	Exterior
eff	Effective
h	Heat
i	Interior
sat	Saturated
v	Vapour
w	Moisture

METHODOLOGY

For the simulations in the coupled CFD/HAM-model and WUFI-2D the next cavity configuration is used, from interior (i) to exterior (e) [Figure 1]: 10 mm gypsum, 100 mm mineral wool, 10 mm Celit-plate [8], 50 mm air cavity and a 100 mm masonry outer layer [Table 1].

Table 1: Material characteristics

	μ	ρ	C	ϕ	λ
Gypsum	8.5	850	850	0.65	0.2
MW	1.3	60	850	0.95	0.04
Celit	6	270	1550	0.83	0.046
Masonry	16	600	850	0.77	0.12

The λ-value is moisture dependent. The sorption-isotherm of these materials is the same as in the material database of WUFI-2D®.

The heat and mass transfer coefficients at the interior and exterior are:

Table 2: Heat and mass transfer coefficients

	Interior	Exterior
α	8	23
β	$\alpha_i.7.10^{-9}$	$\alpha_e.7.10^{-9}$

The heat transfer coefficients are standard used values [9]. The mass transfer coefficients are determined by the heat and mass analogy [9]. The real values of heat and mass transfer coefficients with outer environment depend on many parameters, e.g. humidity of the outer air, air velocity, temperature of the surface, structure of the surface, and so on.

The cavity is a storey high (250 cm). The air velocity (v) at the inlet of the cavity is 0.2 m/s. Measurements show this is a common velocity in such cavity configuration with that cavity depth [10, 11]. A pressure outlet is used for the outlet.

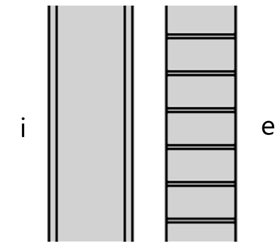

Figure 1 Configuration of the cavity wall.

For the simulations in the coupled CFD/HAM-model the grid is made in Gambit®. The grid density is defined after a Richardson extrapolation. The grid density has an error band of less than 1% for the velocity, the heatflux and the massflux. The total amount of cells for the grid is 95000 (190*X*500). This grid was used for these simulations. The grid density is larger at the interface between two different material layers or between a material layer and an air layer than in the center of the material or air layer.

RESULTS AND DISCUSSION

Heat and mass transfer coefficients at the cavity surfaces

The boundary layers at the cavity surfaces develop over the height of the cavity. Low inlet velocity and relatively large temperature gradients result in mixed convection in the cavity. The local velocity is influenced by the buoyancy forces and defines the thickness of the boundary layer. The thickness of the boundary layer in turn defines the local heat and mass transfer. The thicker the boundary layer, the more difficult the heat and moisture transfer.

First the heat/mass-analogy is examined for mixed convection in a cavity with equal boundary conditions (temperature and mass fraction) for the inner and the outer layer. Secondly a cavity with different boundary conditions for both layers will be examined. To reduce the calculation time, a steady state simulation is made with a constant Θ and Y on each cavity layer.

To simulate the impact of the different boundary condition three cases are compared [Table 1]. The temperature (Θ) and the water vapour mass fraction (Y) of the ventilation air are respectively 22°C and 0,00324. First the case with different conditions on both cavity layers will be simulated. For the second case the temperature and the mass fraction will be increased on the outer wall (R (right)) and for the third case the mass fraction will decrease on the outer wall (R (right)).

Table 3: Boundary conditions

	Θ (L)	Y (L)	Θ (R)	Y (R)
CASE1	20	0,00995	26	0,01424
CASE2	20	0,00995	30	0,0179
CASE3	20	0,00995	30	0,01424

The heat and mass transfer coefficients are defined by:

$\alpha = \frac{q}{(T_s - T_{inlet})}$ and $\beta = \frac{g}{(p_{v,s} - p_{v,inlet})}$, with T_s and $p_{v,s}$ the local surface temperature and the local surface vapour pressure and T_{inlet} and $p_{v,inlet}$ the constant inlet temperature and constant vapour pressure of the cavity.

For equal boundary conditions (constant Θ and *Y*) on both layers, the heat and mass transfer coefficients are identical on both cavity surfaces [not in figure 2].

For different boundary conditions on both layers, the heat and mass transfer coefficients are different at both surfaces (L and R) [Figure 2]. This can be explained by the asymmetric flow in the cavity caused by buoyancy. Near the hot wall the air will rise faster than near the colder wall, since hot air is less dense than cold air. Humid air is also less dense than dry air since the molar weight of water molecules is less than that of air. The temperature difference has the biggest influence on the buoyancy forces and the local velocity and just a small influence is a result of the increase of the RH. The local higher velocity at the hot and humid surface caused by buoyancy results in a higher heat and mass transfer coefficient.

Higher in the cavity, the heat transfer coefficient deviates for the cases with a bigger temperature difference between the cavity layers (CASE2 and CASE3). Simulating on the other hand with a higher velocity at the inlet, this phenomenon does not occur. As a result of the relative higher fraction of natural convection compared to the forced convection, a negative velocity at the colder surface arises. The negative local velocity combined with the use of a constant inlet temperature and mass fraction and the increase of temperature and humidity can probably explain this local instability.

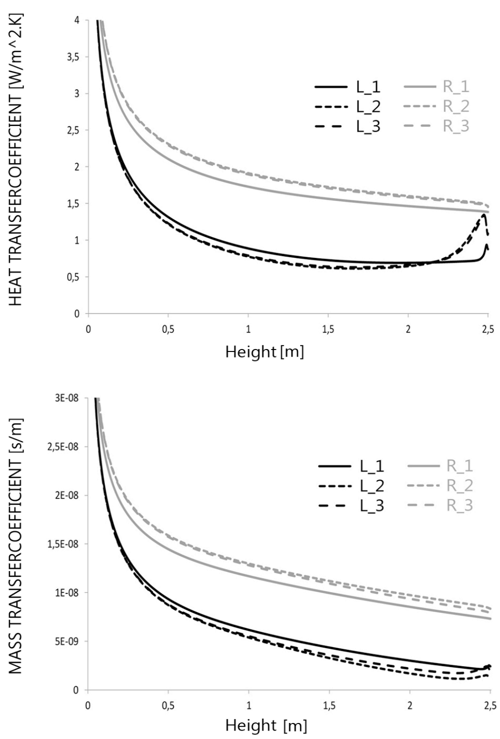

Figure 2 Heat and mass transfer coefficients on the left (L) and the right (R) cavity layer.

For equal boundary conditions on both layers, the heat/mass-analogy ($\frac{\beta}{\alpha} = C^t = 7E-9$) still counts as a result of the large local velocities at the boundaries and because of that large local velocity, a small increase of the humidity and temperature of the air in the cavity. For different boundary conditions on the other hand, the heat/mass-analogy counts at lower heights in the cavity, but not higher in the cavity [Figure 3]. That's a possible result of the increase of the humidity and temperature of the air higher in the cavity and the use of a constant inlet temperature and vapour pressure and also because of the development of the profile of the velocity over the height of the cavity. The main reason is the lower velocity on the colder cavity wall (L), because on the colder cavity wall the natural convection dominates the forced convection. Thus in a vertical cavity, the heat/mass-analogy does not counts at all when the local velocity is too small as a result of natural convection or a low inlet velocity.

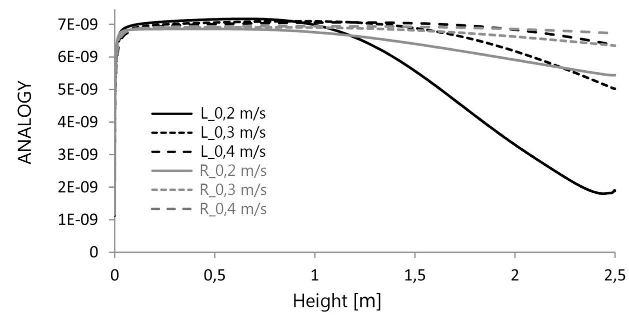

Figure 3 Heat/mass-analogy on the left (L) and the right (R) cavity layer

Long-wave radiation in the cavity

The analysis in the previous paragraph neglected the influence of radiation heat exchange in the cavity. However, at large temperature differences between both walls, this influence can be significant. To examine the influence among the cavity layers as a result of the long-wave radiation in a cavity, a simulation of a summer day in the coupled CFD/HAM-model is used. The boundary conditions at the outside (Θ, RH and short-wave radiation) are varying in time. A comparison was made with and without long-wave radiation in the cavity.

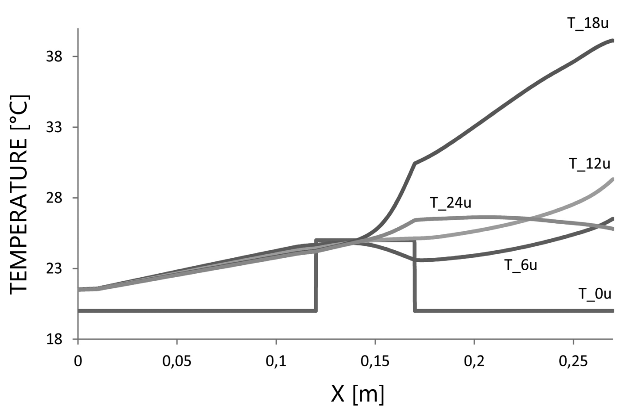

Figure 4 Temperature distribution in the cavity without long-wave radiation at different times over a day.

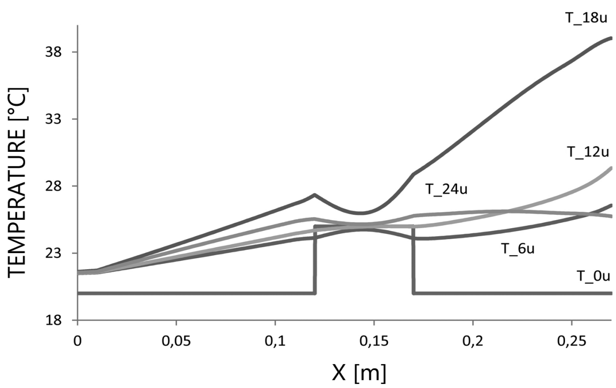

Figure 5 Temperature distribution in the cavity with long-wave radiation at different times over a day.

When the effect of long-wave radiation is not taken into account [Figure 4], the temperature on the cavity surfaces of the Celit-plate is different from that of the masonry layer, as a result of the external short-wave radiation of the sun that heats up the masonry wall. When long-wave radiation is taken into account [Figure 5] the temperature on the cavity surfaces of the Celit-plate becomes equal to that of the masonry layer.

The effect of the long-wave radiation in cavities is important to make a good prediction for the mould risk, because a change in temperature results in a change in relative humidity. At higher velocities on the other hand, the long-wave radiation will be less important because the relative amount of convective heat transfer will be larger than the amount of long-wave radiation heat transfer.

Ventilated cavity walls in WUFI-2D®

The previous section shows that in reality the temperatures at both sides of the cavity equalize. As a result of the equal temperatures, the heat and mass transfer coefficients are approximately equal on both surfaces of the cavity layers. Because of this WUFI [7] uses a λ_{eff}- and a μ_{eff}-value for the air layer, measured in a case of only natural convection. The λ_{eff}-value combines conduction, convection and long-wave radiation. The μ_{eff}-value combines diffusion and convection. For small cavities, the amount of conduction is bigger. For broad cavities the amount of convection is bigger. The amount of long-wave radiation is equal for all cavities widths.

To simulate the effect of ventilation, WUFI adds an extra heat and moisture source at the air layer, depending on the expected air change ratio (ACR). The bigger the ACR, the bigger the heat and moisture source, linked to the in- or outdoor conditions [7]:

$$S_h = h_v \nabla g_v + ACR.\rho.(h_e - h_{cav})$$
$$S_w = ACR.(\rho_{v,e} - \rho_{v,cav})$$

To check if the approach WUFI makes is reasonable, a simulation in WUFI-2D and the coupled CFD/HAM-model is compared [Table 4].

Table 4: Boundary conditions

	Inner layer	Inlet Cavity	Outer layer
Θ [°C]	20	25	30
RH [%]	50	60	80

The temperature and relative humidity outside are the same as in the air cavity. For the inside boundary conditions, Θ is 21°C and the RH is 50%.

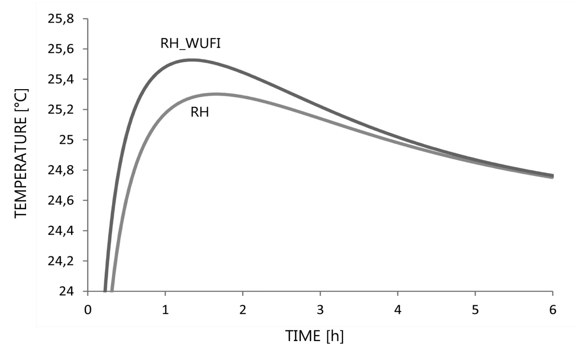

Figure 6: Surface average Θ in the Celit-plate.

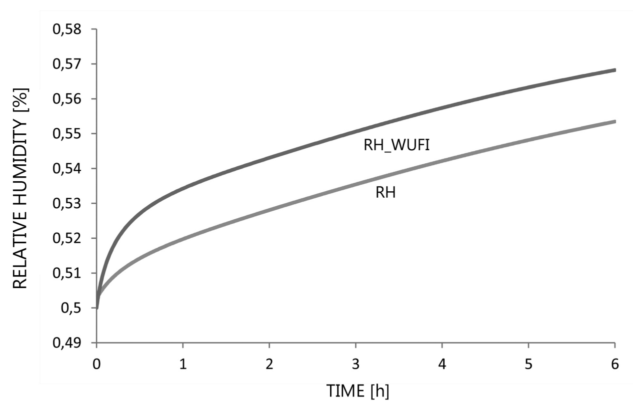

Figure 7: Surface average RH in the Celit-plate.

Comparing the Θ and RH in the Celit-plate for a 6 hours simulation, an initially over-estimation of the increase is identified [Figures 6 and 7]. As a result of the temperature difference between both cavity layers, the profile of the velocity redistributes. On the colder surface (Celit-plate) the velocity due to natural convection has an opposite direction compared to the velocity due to forced convection. The total velocity near the Celit is the superposition of both velocities. This means that the total velocity is locally smaller near the Celit. WUFI does not take that in account. As a result the convective transfer predicted in WUFI near the Celit will be higher than that predicted by the coupled CFD/HAM model.

This means that the approach proposed in [7] is only valid when the temperatures on both sides of the cavity are equal. When the temperatures are different, the local heat and mass transfer coefficients are different. As a result of these different temperatures, an over-estimation of the heat and moisture fluxes on the colder cavity layer is made. After a period of time, when the temperatures on both sides are approximately equal, the change in temperature and relative humidity per time step are equal in the coupled CFD/HAM-model and WUFI-2D. That implies that when the local heat and mass transfer coefficients are equal as a result of the same temperature, the model in WUFI-2D gives equal results as the coupled CFD/HAM-model.

During simulations there are different possible reasons for a temperature difference between the surfaces of both cavity layers:

- An initial temperature difference for the start conditions.
- Extreme heat fluxes from the sun on the outer layer or extreme heat losses to the sky in clear winter nights.
- Bad or little insulation of the inside wall, heats up the inside cavity layer.
- The cavity configuration and the material characteristics such as the heat capacity and the thermal conductivity can determine the wall temperatures. For example materials with high heat capacities will heat up slow and the temperature difference in the cavity will be smaller.

In WUFI the λ_{eff}-value is bigger for wider cavities. Making use of the formula: $R = \frac{x}{\lambda_{eff}}$, the resistance is quasi equal for all the cavity widths [Table 5]:

Table 5: λ_{eff}-value and total heat resistance of the air layer for different cavity widths.

x	λ_{eff}	R
0.010	0.071	0.1408
0.020	0.13	0.1538
0.040	0.23	0.173
0.100	0.59	0.1695

This is because the heat transfer in the cavity is mostly determined by radiation, which is independent of the cavity width. On the other hand the vapour transport resistance in the materials is much higher than in the air, so mass transport from and to the walls is mostly determined by the material properties and less by convection and conduction in the air. Thus a wrong estimate of the μ_{eff}-value will not have severe consequences for the model outcome.

Influence of a cavity layer with a high relative humidity

As a result of the equal temperatures on the surfaces of both cavity layers, there will be no influence of the boundary layer of temperature of the outer cavity layer on the inner cavity wall. There can however be differences in relative humidity between both cavity layers.

To define the effect of a humid outer layer on a less humid inner layer the coupled CFD/HAM-model will be used to simulate a case [Table 6].

Table 6: Initial conditions

	Inner layer	Inlet cavity	Outer Layer
Θ	20	20	20
RH	51	50	80

With an equal initial temperature over the cavity wall, one can see that RH decreased less at 2 m (2) than at 1 m (1) in the Celit-plate [Figure 8].

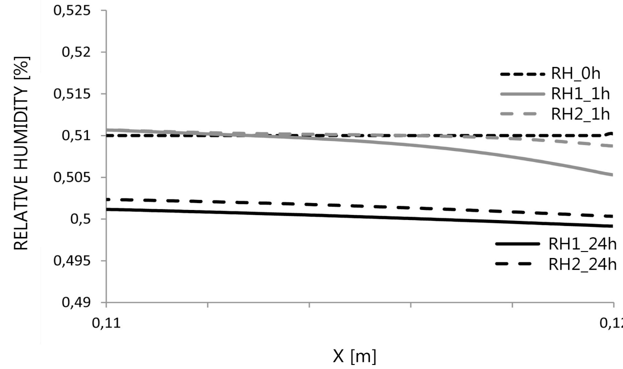

Figure 8: Influence of the masonry wall on the local RH in the Celit-plate (x=0,11:insulation side and x=0,12:cavity side).

At lower heights in the cavity, the boundary layer at the brick side is thinner (developing boundary layer), so the drying of the cavity layer is bigger. Higher in the cavity the boundary layer is thicker, so the drying of the cavity layers is smaller. Overall however, the influence is limited. After one hour, the RH at the cavity surface of the inner layer (at x=0.12m) decreases. This means that after a while the influence decrease and the RH in the Celit-plate becomes the same as the inlet conditions.

The reason for the bigger initial influence is because of the higher initial RH at the cavity surface of the brick. When the brick is drying out, the RH in the air layer at the brick side will be smaller, so the influence will be smaller. If the RH of the brick wall should by constantly 80%, the influence on the inner layer is greater after 24h [Figure 9].

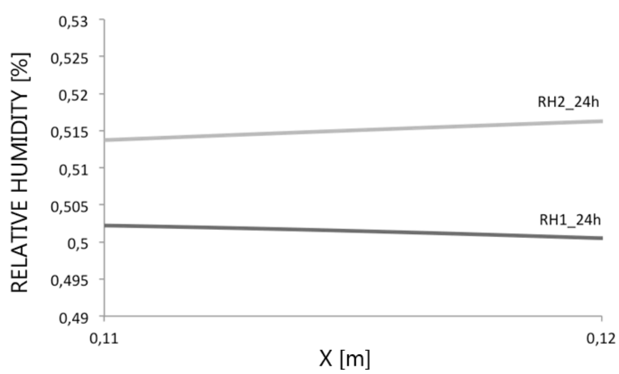

Figure 9: Influence of the masonry wall with a constant RH of 80% on the local RH in the Celit-plate (x=0,11:insulation side and x=0,12:cavity side).

If the initial RH of the outer layer increases from 80% to 100%, for example because of an intense rain shower, the influence can be greater. The problem is that the coupled CFD/HAM-model only simulates vapour transport and no liquid transport, so simulations with humidity near 100% are not possible with the current model. Therefore WUFI-2D can be used to examine the difference in drying behaviour between difference materials.

All of the cases are 10 cm by 10 cm and consist of three adiabatic boundaries and one non-adiabatic boundary. For the heat and mass transfer coefficients at the non-adiabatic boundary between the material and the air, α=2 and $\beta=\alpha.7.10^{-9}$. The initial conditions of the material and the air are listed in [Table 7]:

Table 7: Boundary conditions

	Θ	RH
Material	20	100
Air	20	80

The Θ and RH of the air stay constant over the time. The RH on the surface of the three different materials (masonry, OSB and gypsum board) is compared [Figure 10]:

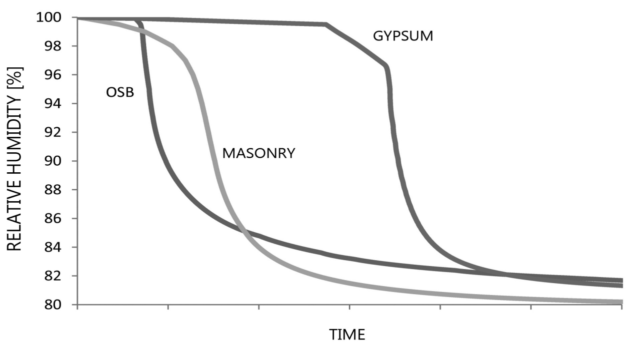

Figure 10 Relative humidity at the surface of the material samples in function of the time.

Gypsum conserves longer his RV round 100%, than the other materials. At a RH round 100%, gypsum loses its strength and stiffness and is therefore not interesting to use as outer layer. OSB conserves longer his RH round 100% at the surface compared to masonry. That is a result of the combination of:

- The sorption-isotherm [Figure 11]
- The moisture permeability [Figure 12]
- w_{sat} [Figure 12]

The combination of both phenomena will lead to a longer conservation of the RH of 100% at the surface than is the case for a brick surface. As a result of that, the influence will be higher on the RH of the other cavity layer. The OSB-plate has a higher w_{sat} and strong increase of the humidity at a RH of nearly 100%. For masonry, the w_{sat} is smaller, so less moisture has to be removed to decrease the RH.

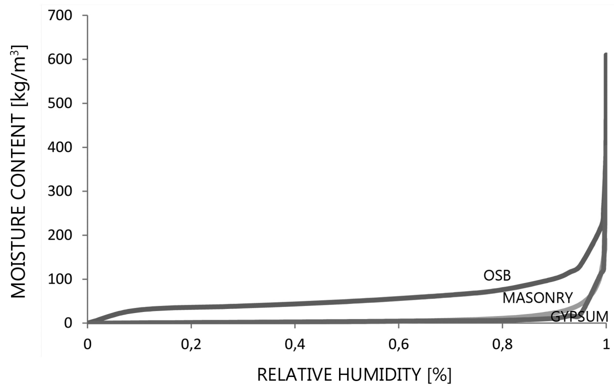

Figure 11 Sorption-isotherm of OSB, masonry and gypsum.

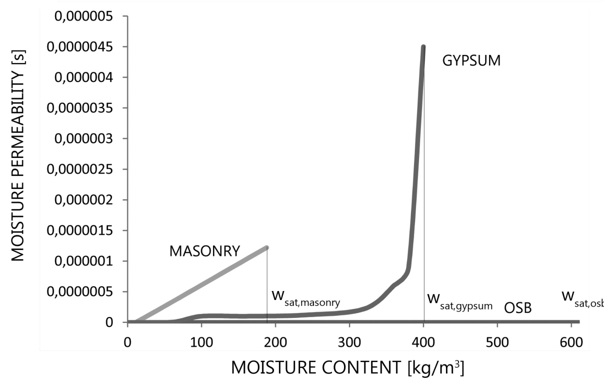

Figure 12 Moisture permeability (K) of OSB, masonry and gypsum.

An outer layer built up of a material with a high w_{sat} and high moisture permeability holds longer a RH of 100% at the surface and has, for that reason, a bigger influence on the inner layer. Also the thickness of the layer and the boundary conditions outside will influence the drying of the layer. The K-value of OSB is not equal to zero but very low (10^{-12} s).

CONCLUSION

For the simulation of ventilated cavity walls, the effect of the long-wave radiation in the cavity cannot be ignored. The effect of the long-wave radiation results in more equal temperatures on both surfaces of the cavity layers. This is a result of an extra heat exchange between the surfaces of the cavity layers. This phenomenon of equal temperatures results in a specific approach in WUFI-2D to simulate ventilated air cavities. If the temperature is however not equal, the approach in WUFI-2D makes an over-estimation of the heat and mass transfer on the colder cavity layer. There are different possible reasons for a temperature difference between the surfaces of both cavity layers:

- An initial temperature difference for the start conditions.
- Extreme heat fluxes from the sun on the outer layer.
- Bad or little insulation of the inner wall heats up the inner cavity surface.

- The cavity configuration and the material characteristics such as the heat capacity and the heat conductivity define how fast temperature of a cavity wall changes.

As a result of the equal temperatures on the surfaces of both cavity layers, there will be no influence of the outer cavity layer on the inner. There are however differences in relative humidity between both cavity layers. The outer cavity layer has indeed an influence on the inner cavity layer. The size of influence depends on the initial moisture content, the sorption-isotherm and the moisture permeability of the outer cavity layer.

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