Coupled Heat and Moisture Transfer in Building Components - Implementing WUFI® Approaches in COMSOL Multiphysics®

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Abstract: Calculating time dependent heat and moisture transport trough building components are important tasks in the area of building physics. A well known and worldwide used commercial software for this is WUFI®. From the scientific point of view the restricted access to governing equations is nevertheless a drawback of this software.
In the present paper it is shown how the physical approaches used in WUFI are implemented in COMSOL Multiphysics® using the Partial Differential Equation interface. The COMSOL model is evaluated with two different benchmarks for heat and moisture simulations and WUFI results itself.
It is shown, that the COMSOL model delivers good results in accordance with the benchmarks and with WUFI. However, slight deviations between COMSOL and WUFI results can occur if the moisture load on the construction is very high.

Keywords: heat moisture transport, building physics, timber flat roof

1. Introduction

Calculating time-dependent heat and moisture transports trough building components are important tasks in the area of building physics. Different approaches can be used to investigate the long time behaviour of building elements under fluctuating conditions [2,3,8,10]. Beside calculation programmes, which are used only by scientists for research purposes, there are also commercial programms available. A well known and worldwide used commercial software for calculating the coupled heat and moisture transfer in building components is WUFI®, developed at the Fraunhofer-Institute for Building Physics [8]. It is used for research purposes and also by designers for commercial tasks. From the scientific point of view the restricted access to governing equations is nevertheless a drawback of WUFI.

In this paper it is shown how the physical approaches used in WUFI are implemented in COMSOL Multiphysics® using the Partial Differential Equation (PDE) interface. The COMSOL results are evaluated with different benchmarks and WUFI results itself.

2. Governing Equations

In the following section the governing equations for the heat and moisture transfer trough building components are presented. It is also shown, how the boundary conditions are generated.

2.1 Transport processes

The coupled heat and moisture transport processes are calculated from WUFI in the following way [8]:

$$\frac{dH}{dT}\frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) + h_v \nabla\left[\delta_p \nabla(\varphi p_{sat})\right] \quad (1)$$

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

dH/dT	Heat storage capacity in J/m³.K
$dw/d\varphi$	Moisture storage capacity in kg/m³
λ	Thermal conductivity in W/m.K
D_φ	Liquid conduction coefficient in kg/m.s
δ_p	Water vapour permeability of the building material in kg/m.s.Pa
h_v	Evaporation enthalpy of water in J/kg
p_{sat}	Water vapour saturation pressure in Pa
T	Temperature in K
φ	Relative humidity

In this approach the temperature and the relative humidity are the driving potentials. Both potentials are affecting both transport processes, so they have to be deviated with respect to space in both equations.

$$\delta_p \nabla(\varphi p_{sat}) = \delta_p \varphi \frac{\partial p_{sat}}{\partial T} \nabla T + \delta_p p_{sat} \nabla\varphi \quad (3)$$

With equation (3) the heat and moisture transport equations can be described in the following way:

$$\frac{dH}{dT}\frac{\partial T}{\partial t} = \nabla[(\lambda + h_v \mathrm{\delta_p \varphi} \frac{\mathrm{dp_{sat}}}{\mathrm{dT}})\nabla T + h_v \delta_p p_{sat} \nabla\varphi] \quad (4)$$

$$\frac{dw}{d\varphi}\frac{\partial \varphi}{\partial t} = \nabla[\mathrm{\delta_p \varphi} \frac{\mathrm{dp_{sat}}}{\mathrm{dT}} \nabla T + (D_\varphi + \delta_p p_{sat})\nabla\varphi] \quad (5)$$

with

$$\frac{dw}{d\varphi} = \xi \quad (6)$$

$$D_\varphi = D_w \xi \quad (7)$$

$$\frac{dp_{sat}}{dT} = \frac{M_w h_v}{RT^2} p_{sat} \quad (8)$$

ξ	Moisture storage capacity in kg/m³
D_φ	Liquid conduction coefficient in kg/m.s
D_w	Liquid transport coefficient m²/s
D_{ws}	Liquid transport coefficient for suction in m²/s
$\frac{dp_{sat}}{dT}$	Slope of water vapour saturation pressure curve by the Clausius-Clapeyron relation [3] in Pa/K
M_w	Molar weight of water in kg/mol
h_v	Evaporation heat of water in J/kg
R	Universal gas constant in J/mol.K

The water vapour permeability of the building material can be calculated by the following relation:

$$\delta_p = \frac{\delta}{\mu} \quad (9)$$

with

$$\delta = 2{,}0 \cdot 10^{-7} T^{0.81} / P_L \quad (10)$$

δ	Water vapour permeability of stagnant air in kg/m.s.Pa
μ	Water vapour diffusion resistance factor of the building material
P_L	Ambient atmospheric pressure in Pa

Neglecting the enthalpy change caused by icing and the dependence of the water vapour content in the building material pores, we can calculate the heat storage capacity by the following equation [3]:

$$\frac{dH}{dT} = (c_s + \frac{1}{\rho_s} c_w w)\rho_s \quad (11)$$

c_s	Specific heat capacity of dry building material in J/kg.K
c_w	Specific heat capacity of water in J/kg.K
w	Water content in kg/m³
ρ_s	Bulk density of the dry building material in kg/m³

Rearrange the transport equations (4) and (5) into matrix notation, we finally get

$$\begin{bmatrix} \lambda + h_v \mathrm{\delta_p \varphi} \frac{\mathrm{dp_{sat}}}{\mathrm{dT}} & h_v \delta_p p_{sat} \\ \mathrm{\delta_p \varphi} \frac{\mathrm{dp_{sat}}}{\mathrm{dT}} & D_\varphi + \delta_p p_{sat} \end{bmatrix} \begin{bmatrix} \nabla^2 T \\ \nabla^2 \varphi \end{bmatrix} = \begin{bmatrix} \left(c_s + \frac{1}{\rho_s} c_w w\right)\rho_s & 0 \\ 0 & \xi \end{bmatrix} \begin{bmatrix} \frac{\partial T}{\partial t} \\ \frac{\partial \varphi}{\partial t} \end{bmatrix} \quad (12)$$

2.2 Boundary conditions

The heat exchange at the building elements surface can be calculated using the following relation [8]:

$$q = \alpha(T_{air} - T_{suf}) \quad (13)$$

q	Heat flux density in W/m²
α	Total heat transfer coefficient in W/m²K
T_{air}	Temperature of the ambient air
T_{surf}	Temperature of the building elements surface

with

$$\alpha = \alpha_c + \alpha_r \quad (14)$$

α_c	Convective heat transfer coefficient in W/m².K
α_r	Radiation related heat transfer coefficient in W/m².K

To consider the radiation effects (long-wave (thermal), short-wave (solar)) on the exterior surface the equivalent exterior temperature *T** can be used [7].

$$q_e = \alpha^*(T^* - T_{surf}) \tag{15}$$

q_e	Exterior heat flux density in W/m²
T^*	Equivalent exterior temperature in K

If the "Explicit Radiation Balance" mode to consider the radiation effects (e.g. nighttime overcooling) is applied in WUFI, only the convective part of the total heat transfer coefficient is used.
In this case, WUFI calculates the convective heat transfer coefficient by subtracting 6.5 W/m².K from the total heat transfer coefficient.

$$\alpha_c = \alpha - 6{,}5[W/m^2.K] \tag{16}$$

To calculate the heat flux density at the exterior surface we use the following relation to consider the radiation effects:

$$q_e = \alpha_c(T^* - T_{surf}) \tag{17}$$

According to [7] T^* can be calculated by the following correlation:

$$\alpha_c(T_{air} - T^*) + I = 0 \tag{18}$$

I	Net radiation to the building components surface in W/m²

To calculate the net radiation an approach from [6] is applied, which is also used in WUFI. In the following equations the terrestrial radiation is however not considered. It is not necessary for the later on investigated flat roof construction.

$$I = aI_s + \varepsilon I_l - I_e \tag{19}$$

a	Short-wave absorptivity
I_s	Incoming short-wave solar radiation in W/m²
ε	Long-wave emissivity and absorptivity
I_l	Incoming long-wave radiation in W/m²
I_e	Long-wave emission in W/m²

with

$$I_s = I_{s,dir} + g_{atm}I_{s,diff} \tag{20}$$

$$I_l = g_{atm}I_{l,atm} \tag{21}$$

$$I_e = \varepsilon\sigma {T^*}^4 \tag{22}$$

$$g_{atm} = cos^2\left(\frac{\beta}{2}\right) \tag{23}$$

$I_{s,dir}$	Direct solar radiation in W/m²
g_{atm}	Atmospheric view factor
$I_{s,diff}$	Diffuse solar radiation in W/m²
$I_{l,atm}$	Atmospheric long-wave radiation in W/m²
σ	Stefan-Bolzmann constant in W/m².K^4
β	Inclination of the building elements surface (90° for a vertical wall)

To get a linear approach of the total radiation, equation (22) is linearised by a first-order Taylor series approximation [6].

$$I_{e,lin} = \varepsilon\sigma T_0^4 + 4\varepsilon\sigma T_0^3(T^* - T_0^*) \tag{24}$$

$I_{e,lin}$	Linearised long-wave emission in W/m²
T_0^*	Equivalent exterior temperature of the previous timestep in K

Inserting equations (20), (21) and (24) into equation (19) and solve equation (18) for the equivalent outdoor temperature we get:

$$\begin{aligned} T^* = \big[&\alpha_c T_{air} + a(I_{s,dir} + g_{atm}I_{s,diff}) \\ &+ \varepsilon g_{atm}I_{l,atm} + 3\varepsilon\sigma {T_0^*}^4\big] \\ &\cdot \frac{1}{\alpha_c + 4\varepsilon\sigma {T_0^*}^3} \end{aligned} \tag{25}$$

The moisture flux through the building surfaces can be calculated in the following way [8]:

$$g = \beta(p_{air} - p_{surf}) \tag{26}$$

g	Vapour diffusion flux density in kg/m².s
β	Water vapour transfer coefficient in kg/m².s.Pa
p_{air}	Partial pressure of water vapour in the ambient air in Pa
p_{surf}	Partial pressure of water vapour of the building elements surface in Pa

with

$$\beta = 7 \cdot 10^{-9}\alpha_c \tag{27}$$

3. Use of COMSOL Multiphysics

3.1 Transport processes

To implement the governing equations (12) in COMSOL Multiphysics, we use the PDE (c) interface. All coefficients, except the diffusion, damping and mass coefficients respectively are set to zero. In COMSOL notation we have for each material layer:

$$d_a \frac{\partial u}{\partial t} - c\nabla^2 u = 0 \qquad (28)$$

$$u = [T, RH]^T \qquad (29)$$

d_a	Mass coefficient
c	Diffusion coefficient
u	Transport potentials
T	Temperature in K
RH	Relative humidity
^{T}	Transposed

Rearrange equation (28) into matrix notation gives

$$\begin{bmatrix} c11 & c12 \\ c21 & c22 \end{bmatrix} \begin{bmatrix} \nabla^2 T \\ \nabla^2 RH \end{bmatrix} = \begin{bmatrix} d_a11 & d_a12 \\ d_a21 & d_a22 \end{bmatrix} \begin{bmatrix} \frac{\partial T}{\partial t} \\ \frac{\partial RH}{\partial t} \end{bmatrix} \qquad (30)$$

The coefficients *c11,…,c22* and *d_a11,…,d_a22* can be taken from equation (12).

A good description how to implement the governing equations for isothermal cases in COMSOL Multiphysics can be found in [11].

3.3 Material data

Basically, the material data of the WUFI database can be used, but for liquid transport coefficients one has to use semi logarithmical values to enable linear interpolation (e.g. 60 | log10(3E-9)).

4. Model verification

In the following section the results of 1-D COMSOL simulations are compared with different benchmarks for heat and moisture transport simulations and with WUFI simulations.

4.1 EN 15026

The benchmark according to the European Standard EN 15026 [1] deals with the influence of a step change in *T* and *RH* on a specific building material. According to the benchmark, the simulation results have to fall within the confidence intervals (± 2.5 %) of the analytical solutions.

Figure 1 shows the COMSOL results and the confidence intervals (CI) of the benchmark. As can be seen from the graphs, the COMSOL results are within the confidence intervals of the analytical solutions for all time steps investigated.

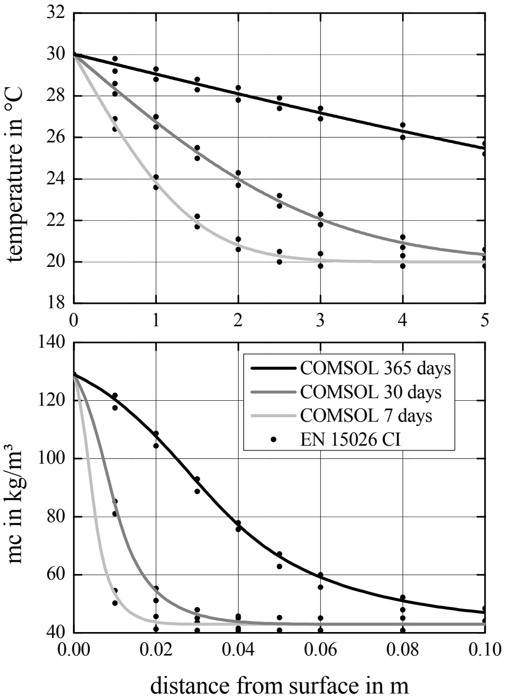

Figure 1: COMSOL results for temperature and moisture content (mc) of the building material as well as associated confidence interval (CI) of the analytic solution according to the EN 15026 benchmark for certain time steps

4.2 HAMSTAD

This benchmark for heat and moisture simulation is a result of the international project HAMSTAD [4]. It deals with the internal condensation on the contact surface of two materials in an insulated flat roof [5]. Figure 2 shows the calculated flat roof with outer moisture sealing, a load bearing layer and an insulation layer at the interior side. The load bearing material A is capillary active while the insulation material B is capillary non-active and has a thermal conductivity 50 times as high as material A. A transient outer climate and steady state indoor climate were used as boundary conditions.

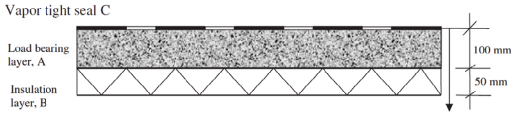

Figure 2: Construction details for the HAMSTAD benchmark [5]

Figure 3 shows the COMSOL results of the moisture content of material A and B in the first simulated year and the corresponding mean value and confidence intervals of the HAMSTAD benchmark. It is shown, that the COMSOL results are within the confidence intervals and close to the mean values. The same holds for material A in the fifth year, which can be seen in Figure 4. The moisture content for material B in the fifth year stays at a very low level and therefore it is not indicated here.

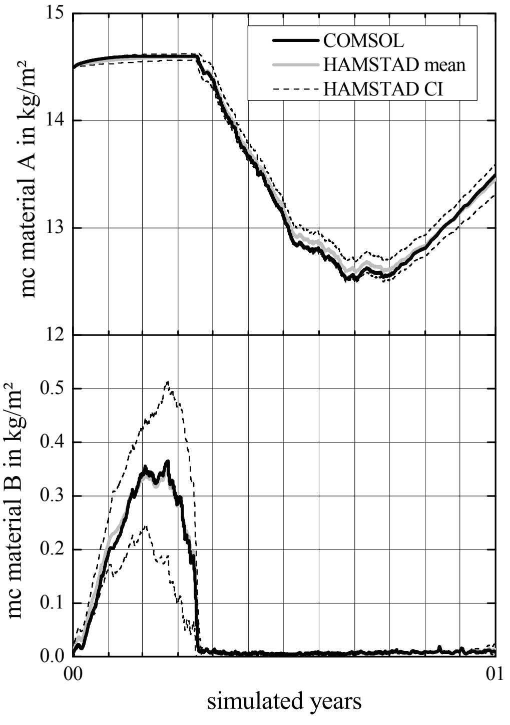

Figure 3: COMSOL results for moisture content (mc) of material A and B as well as mean value and confidence interval (CI) of the HAMSTAD benchmark [5] in the first simulated year

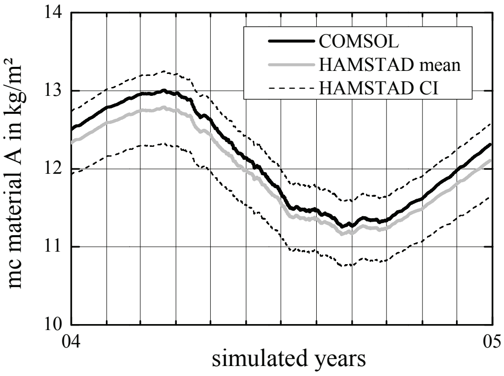

Figure 4: COMSOL results for moisture content (mc) of material A as well as mean value and confidence interval (CI) of the HAMSTAD benchmark [5] in the fifth simulated year

4.3 WUFI

To compare COMSOL results with WUFI results, we calculated a flat roof with vapour tight sealing and wooden cladding at the exterior side (Figure 5).

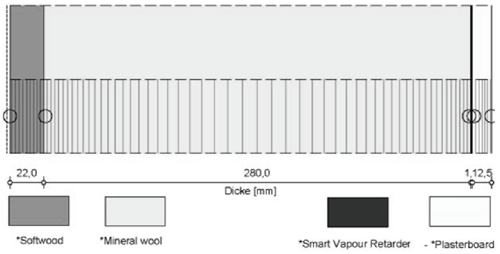

Figure 5: Construction details for the COMSOL/WUFI comparison

We investigated two versions of the flat roof:
Version 1: airtight and sun exposed
Version 2: not airtight and temporarily shaded

With version 2 we create critical conditions for timber flat roofs [9].
Figure 6 indicates the moisture content of the softwood and the whole roof element during the simulated years. The moisture content of the softwood is expressed in % of water (mass) of the oven-dry mass of the softwood. As one can see, the COMSOL results and the WUFI results are nearly identical in version 1. In version 2 where the moisture content of the softwood exceeds the critical value of 20 %, slight deviations between COMSOL and WUFI results occur. The maximum absolute deviation at the highest moisture content is + 5.7 % for softwood and + 6.8 % for the whole construction.

Figure 7 shows the exterior heat flux density simulated by COMSOL and WUFI for the flat roof version 1 in January and July in the tenth year. Deviations are hardly visible in the graphs, the exterior heat fluxes of both simulations are nearly identical.

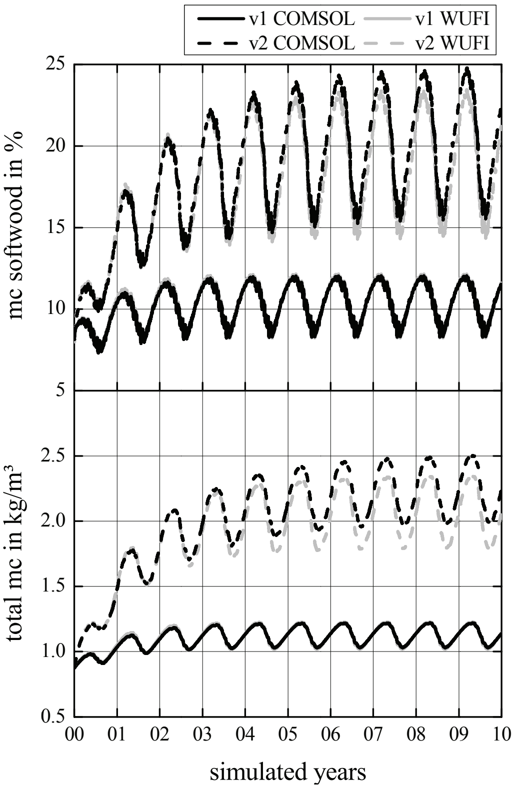

Figure 6: COMSOL and WUFI results for the moisture content (mc) of the softwood and of the total roof construction for both calculated versions

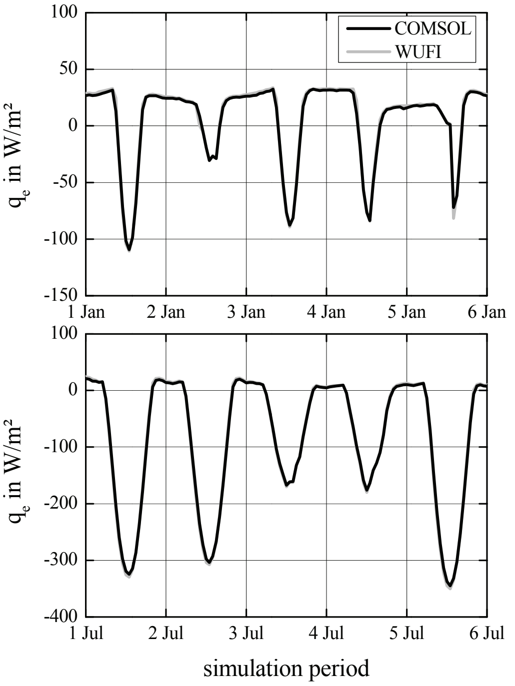

Figure 7: Exterior heat flux density of version 1 in the tenth year

5. Conclusion

This paper describes the governing equations which are necessary to implement the WUFI approaches in COMSOL Multiphysics and evaluate the so created model. It is shown, that the COMSOL model delivers good results in accordance with two different benchmarks for heat and moisture simulations.

The accordance of COMSOL and WUFI results is good as well. However, slight deviations between COMSOL and WUFI results can occur if the moisture load on the construction is very high.

6. References

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