Building physics problems in early modernism and how to solve - A school built by Baumann/Prachenzky (1929/31) as case study (CS5) in 3ENCULT

M. Bianchi Janetti[1], R. Pfluger[1], K. Längle[1], F. Ochs[1], F. Nesi[1], W. Feist[1,2]

ABSTRACT

A 3D model for the hygrothermal simulation of the ceiling-wall connection in a listed school building located in Innsbruck is presented. The model is implemented with the FE program COMSOL Multiphysics in order to estimate the risk of condensation and mold growth in case of application of internal insulation.

The investigated construction is part of the case study CS5 within the EU-Project (seventh framework program) 3ENCULT, a detailed description of the problem and critical evaluation of the simulation results is reported. Valuable recommendations for planners and decision makers in terms of minimal invasive measures will be derived.

Keywords

Hygrothermal simulation, internal insulation, ceiling-wall connection, condensation risk, 3ENCULT

1. Introduction

The renovation of existing buildings according to high energy efficiency standards will represent a significant contribution to the reduction of CO_2-emissions (EPBD Recast 2010).

In particular for the renovation of historical buildings, specific solutions with internal insulation have to be developed. However, such solutions require careful planning in order to avoid condensation risk and/or degradation of the construction. Hence, the study of heat and moisture transfer in construction materials has recently become even more relevant.

Within the EU-project 3ENCULT, focused on developing technologies for the retrofitting of listed building, a 3D model for the simulation of transient heat and moisture transfer in building elements has been developed and implemented with COMSOL Multiphysics. This model has been used to evaluate the condensation and mold growth risk deriving from the application of internal insulation in a listed school building (Innsbruck, 1929/31, Baumann/Prachenzky, the Austrian 3ENCULT case study).

2. State of the art

In the last twenty years several authors developed models describing heat and moisture transfer in porous materials with applications also in the building physics. Numerical solutions have been proposed for calculating temperature and moisture content inside constructions as function of time and position and commercial programs specific for hygrothermal simulations have been developed. In particular, the programs Delphin and WUFI ([1] [2]) are widely used supporting architects and engineers in designing the envelope of buildings. However, these programs are restricted to two dimensional geometries at present.

COMSOL Multiphysics represent a powerful tool for solving a large number of physical problems described by systems of partial differential equations. In particular, as recently shown ([3] [4]), it can be useful also for solving heat and moisture transfer problems inside constructions, although applications to real cases in this area are still rare. One advantage of COMSOL is that also 3D problems can be modeled. The simulation of the ceiling-wall connection presented in this paper is an example of solving practical building physics problems using this program.

3. Theory of Heat and Moisture Transfer in Porous Materials

In this section the model for heat and moisture transfer implemented in COMSOL is described.

3.1 Governing Equations and use of COMSOL Multiphysics

As suggested by other authors ([5], [6], [7]), a macroscopic approach has been chosen since it allows porous construction materials to be treated as homogeneous media. Under this assumption, heat and moisture transfer processes can be described by a system of two partial differential equations derived by imposing the equilibrium balance of mass and energy within an infinitesimal element of volume. For the one-dimensional case the governing equations system assumes the following form:

$$\frac{\partial u}{\partial \varphi}\frac{\partial \varphi}{\partial t}+\frac{\partial}{\partial x}\left(-D_{m,\varphi}\frac{\partial \varphi}{\partial x}-D_{m,T}\frac{\partial T}{\partial x}\right)=0 \tag{1}$$

$$\frac{\partial h}{\partial T}\frac{\partial T}{\partial t}+\frac{\partial h}{\partial \varphi}\frac{\partial \varphi}{\partial t}+\frac{\partial}{\partial x}\left(-D_{e,T}\frac{\partial T}{\partial x}-D_{e,\varphi}\frac{\partial \varphi}{\partial x}\right)=0 \tag{2}$$

The system of equations (1) and (2) can be solved with COMSOL Multiphysics using the PDE mode in the coefficients form.

Temperature T and relative humidity φ are the dependent variables whereas t and x represent time and position. u is the moisture content and h the enthalpy. $D_{m,\varphi}$, $D_{m,T}$, $D_{e,T}$ and $D_{e,\varphi}$ are material specific diffusion coefficients which assume the following form:

[1] University of Innsbruck, Unit for Energy Efficient Buildings, Austria, michele.janetti@uibk.ac.at

[2] Passiv Haus Institut, Germany

$$D_{m,\varphi} = \frac{p_s D_v}{\mu R_v T} - K_l \frac{\partial p_c}{\partial \varphi} \quad (3)$$

$$D_{m,T} = \frac{\varphi D_v}{\mu R_v T} \frac{dp_s}{dT} \quad (4)$$

$$D_{e,T} = \lambda + (h_{lv} + c_{p,v} T) \frac{\varphi D_v}{\mu R_v T} \frac{dp_s}{dT} \quad (5)$$

$$D_{e,\varphi} = (h_{lv} + c_{p,v} T) \frac{p_s D_v}{\mu R_v T} \quad (6)$$

The derivation of the transport coefficients according to the theory of heat and moisture transfer is presented in the following section.

3.2 Material Functions

In this section the material specific functions describing storage and transfer processes are described.

3.2.1 Moisture Storage

The water content u inside a porous material can be represented as function of the relative humidity φ, whereas its dependence from the temperature can be neglected in most cases (see Figure 1).

The relationship between u and φ is described by the water retention curve, which is material-specific and can be obtained in experimental way as shown in [8]. This function has been imported in COMSOL using a linear interpolation method.

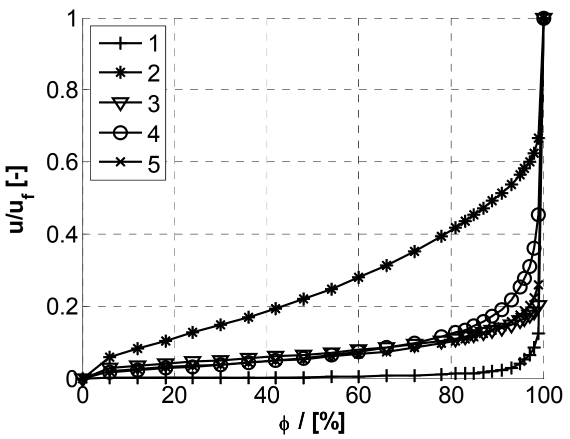

Figure 1 Water retention curve of brick (1), concrete (2), spruce (3), mineralic insulation plaster (4) and plaster (5)

3.2.2 Energy Storage

The energy storage inside a volume element can be described through the following equation:

$$h = \rho_d c_{p,d} T - w \rho_a c_{p,a} T + w \rho_l c_l T + (w_f - w)(h_{lv} + c_{p,v} T) \rho_v \quad (7)$$

where h, ρ, c and T are the enthalpy, the density, the thermal capacity and the temperature respectively. The indices d, a, v and l represent the dry material (including solid matrix and air inside the pores), the air replaced by liquid water, the vapor and liquid phase of water respectively. The volume fraction employed by liquid water w is defined by equation (8):

$$w = \frac{u}{\rho_l} \quad (8)$$

Under the condition of free moisture saturation, w assumes its maximal value w_f.

3.2.3 Moisture Transfer

The mechanisms related to moisture transfer in porous materials are shown in Figure 2.

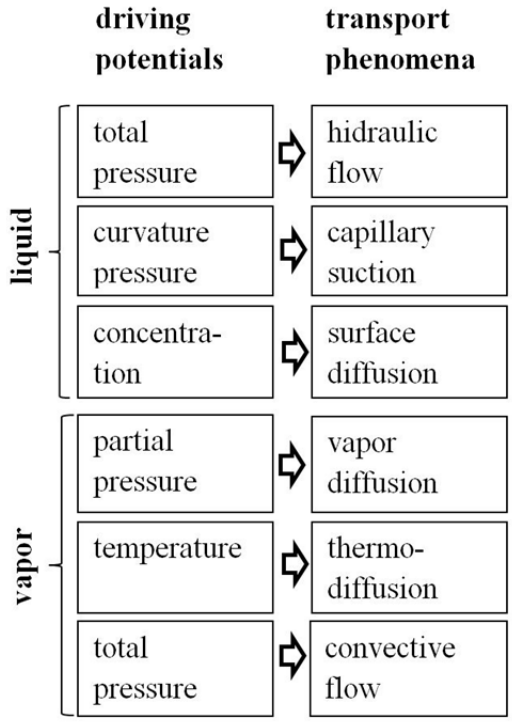

Figure 2 Moisture transfer phenomena in porous materials [8]

As noticed in [6], the mass transfer due to air pressure or hydraulic pressure differences and the effect of the gravity are negligible within the temperature and pressure ranges relevant for the building physics. Considering that the thermal diffusion can be neglected as well, the remaining transfer mechanisms include the vapor diffusion due to the vapor partial pressure gradient and the liquid flux concerning the capillary suction and the surface diffusion.

The diffusive vapor flux takes the following form according to [7]:

$$j_v = -\frac{D_v}{\mu R_v T} \frac{\partial p_v}{\partial x} \quad (9)$$

where p_v represents the partial pressure of vapor, D_v the diffusivity of vapor in air, μ the vapor diffusion resistance factor and T the absolute temperature.

Equation (10) gives the relation between the partial pressure of vapor p_v, the relative humidity φ and the saturation pressure p_s, which is a function of the temperature:

$$p_v = \varphi p_s(T) \quad (10)$$

From (9) and (10) it follows:

$$j_v = -\frac{\varphi D_v}{\mu R_v T}\frac{dp_s}{dT}\frac{\partial T}{\partial x} - \frac{p_s D_v}{\mu R_v T}\frac{\partial \varphi}{\partial x} \quad (11)$$

According to [6] the liquid flux j_l due to the capillary suction gradient can be described by (12):

$$j_l = K_l \frac{\partial p_c}{\partial x} \quad (12)$$

where p_c represents the capillary pressure and K_l the liquid conductivity which is a material specific moisture dependent parameter. K_l depends from the water content and is obtained in an experimental way [8]. In Figure 3 is shown K_l of the materials used in the simulation. Equation (12) can be written in the following form, showing explicit the gradient of φ.

$$j_l = K_l \frac{\partial p_c}{\partial \varphi}\frac{\partial \varphi}{\partial x} \quad (13)$$

The liquid flux represents a significant contribution to the whole moisture transfer for higher moisture contents.

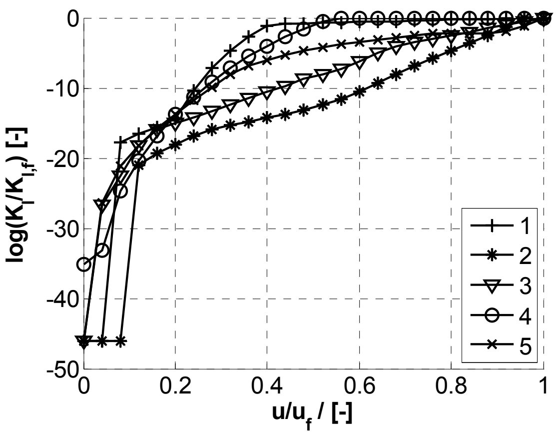

Figure 3 Liquid transfer coefficient of brick (1), concrete (2), spruce (3), mineralic insulation plaster (4) and plaster (5)

3.2.4 Energy Transfer

The energy transfer through a porous material can be described according to [6] by:

$$q = -\lambda \frac{\partial T}{\partial x} + \left(h_{lv} + c_{p,v}T\right)j_v \quad (14)$$

where q represents the total energy flux and λ the real thermal conductivity of the material. The enthalpy flux due to mass transfer is represented by the term $(h_{lv}+c_{p,v}T)j_v$, where j_v represent the vapor flux. The contribute of the liquid flux can be neglected.

The real thermal conductivity of the moist material is a function of the water content, whereas its dependence on the temperature can be neglected for standard building physics problems.

4. Problem description

The school building in Hötting (Innsbruck, Austria) is a typical example of architecture in early modernism with specific building physics problems.

The external walls are crossed by a ceiling with structural function. The material employed for the walls are brick and concrete, whereas the ceiling consists of a wooden floor, a screed, reinforced concrete with hollow bricks between and a plaster layer below. A floor plan and the sections of the wall-ceiling connection are shown in Figure 4.

External insulation for the renovation of the building was not accepted by the local monument protection service, even though it represents the best solution from a technical point of view. However, using internal insulation, a thermal bridge at the ceiling-wall junction cannot be avoided. Hence at this location significant moisture accumulation has to be expected. Moisture is transported by means of diffusion and convection through the hollow bricks to the wall surface and the beam ends.

Structural damage due to corrosion of the steel in the reinforced concrete has to be prevented, moreover mold growth have to be avoided.

This complex heat and moisture transfer problem can be solved by using 3D-models only.

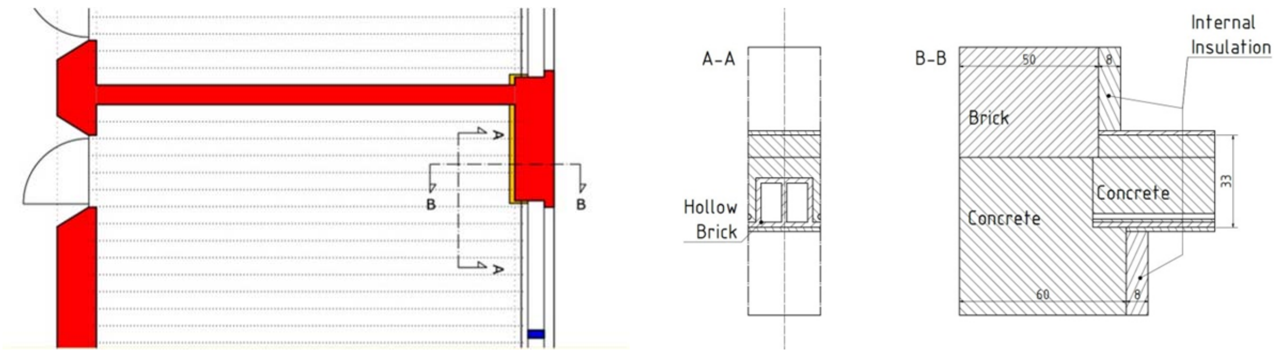

Figure 4 Floor plan detail (left) and Ceiling-wall section (right), School in Hötting, Innsbruck

Table 1 Material data

Material	ρ [Kg/m^3]	c [J/(kg K)]	λ [W/(m K)]	μ [-]	u_f [Kg/m^3]
Brick	1979.11	833.761	0.996	45.107	240.6
Concrete	2320.2	850	2.1	110	142.99
Mineralic Insulation Plaster	610.7	1000	0.035	7	490
Spruce	450	2500	0.13	40	600
Plaster	1567.8	1000	0.7	10.58	407
Air	1.2	1006	0.026*	0.5*	-

*Equivalent values taking convection into account

5. Simulation of the ceiling

In this section, the input data and the simulation results are described. The meshing of the 3D Model is shown in Figure 5.

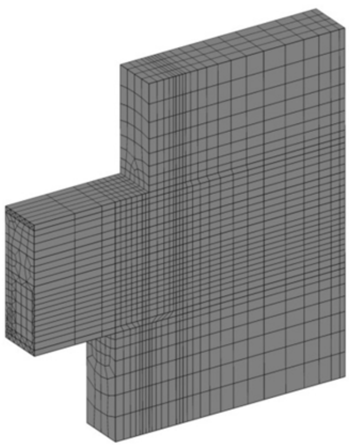

Figure 5 FE mesh

5.1 Material Data

The material data used in the simulation are reported in Table 1. All material data and functions applied in this paper are taken from the database of the program Delphin [1].

The convection contribution to the moisture and heat transfer through the hollow bricks is taken into account using increased diffusion coefficients for heat and mass transfer. Equivalent values of thermal conductivity and vapor diffusion resistance can be estimated knowing the dimensions of the air cavity and the main direction of the heat flux. In alternative to the use of equivalent diffusion coefficients a CFD calculation can be performed. This second way to model the problem is more realistic. However it is more complex and requires higher computational effort.

5.2 Boundary and Start Conditions

On the external surfaces time dependent boundary conditions of the third kind are imposed. For the sake of simplicity, the local climatic data (temperature and relative humidity) are approximated with sinus curves presenting annual period, as shown in Figure 6 and Figure 7. The influence of the rain and of the radiation can be examined but it is not yet included in the simulation presented in this work. On the internal surfaces constant values of temperature and relative humidity are imposed (see Table 2).

The start conditions are 20 °C and 80 % relative humidity. The simulation covers a real time of several years, so that the influence of the start conditions on the final results becomes negligible.

Table 2 Boundary conditions

Parameter	Unit	Internal	External
θ	[°C]	20	$T_a(t)$
φ	[-]	50	$φ_a(t)$
α	[W/(m^2 K)]	6	25
β	[s/m]	3e-08	2e-06

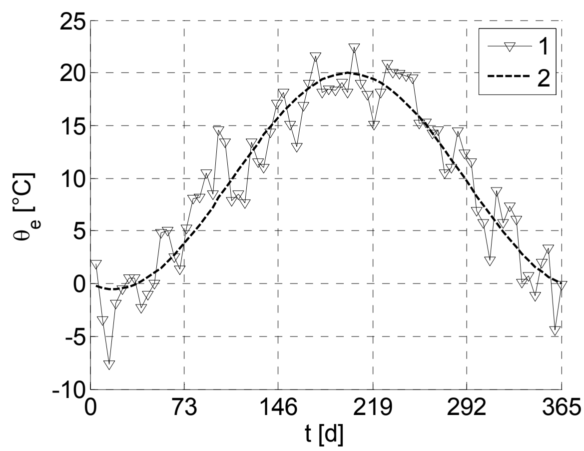

Figure 6 External temperature. 1: climatic data Innsbruck, METEONORM; 2: periodic approximation

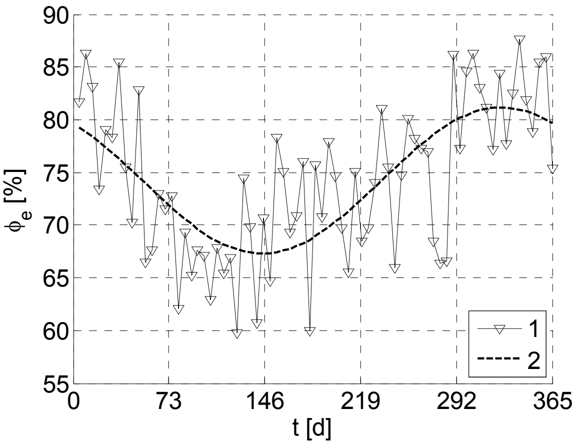

Figure 7 External relative humidity. 1: climatic data Innsbruck, METEONORM; 2: periodic approximation

5.3 Results

As result of the simulation the moisture distribution (water activity, a_w value) inside the construction is obtained, allowing to predict if water condensation and corrosion problems occur. In Table 3 the simulated variants are reported (φ_i is the internal relative humidity).

Table 3 Simulation variants

Case	Thermal Conductivity Internal Insulation [W/(m K)]	φ_i [%]
1	-	50
2	0.1	50
3	0.035	50
3a	0.035	30

Firstly, the actual state of the building, without any insulation (case 1) is considered. The water activity distribution inside the wall is shown in Figure 8. This case does not present any problem concerning condensation formation, since the water activity stay under 80% over the whole period even at the most critical position (see Figure 10). Mold germination could occur, however just in very limited form.

The influence of the application of internal insulation is shown in Figure 9 (case 3). As expected the water activity increases, basically due to vapor diffusion from the internal ambient, since the wall remains cool during the winter period. The critical position is the wall surface bordering the hollow bricks of the ceiling. The maximal value point is identified in Figure 9 and the corresponding trends of temperature and water activity are shown in Figure 10. According to these results, water condensation is excluded also in this case; however there are favorable conditions for mold growth and corrosion (see Figure 11).

It can be observed that reducing the internal relative humidity, these problems would be excluded (case 3a, Figure 11 right). Considering that, the installation of a ventilation system is recommendable.

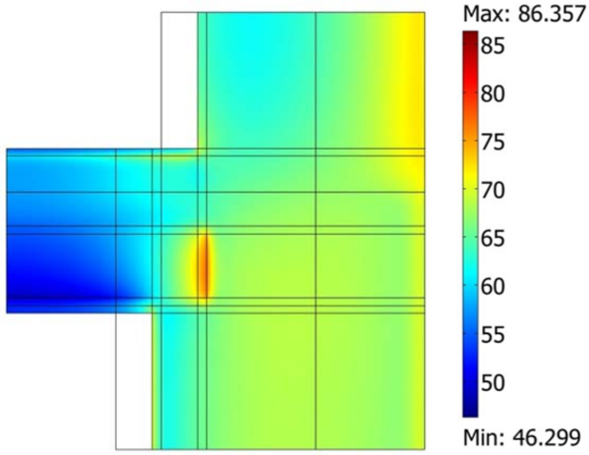

Figure 8 Water activity distribution on December 31st (case 1, values in %)

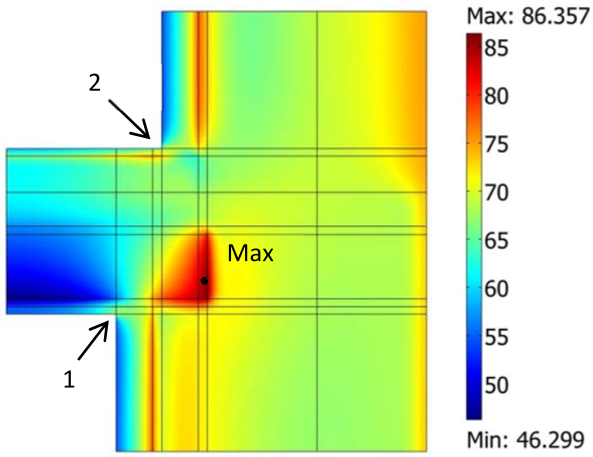

Figure 9 Water activity distribution on December 31st (case 3, values in %). The yearly evolution at point "Max", "1" and "2" is shown in Figure 10, Figure 11 and Figure 12.

The sensibility of the results concerning the thermal conductivity of the internal insulation is investigated. With reduced thermal resistance of the insulation, a moderate reduction of the water activity can be observed (compare case 2 with case 3, Figure 10).

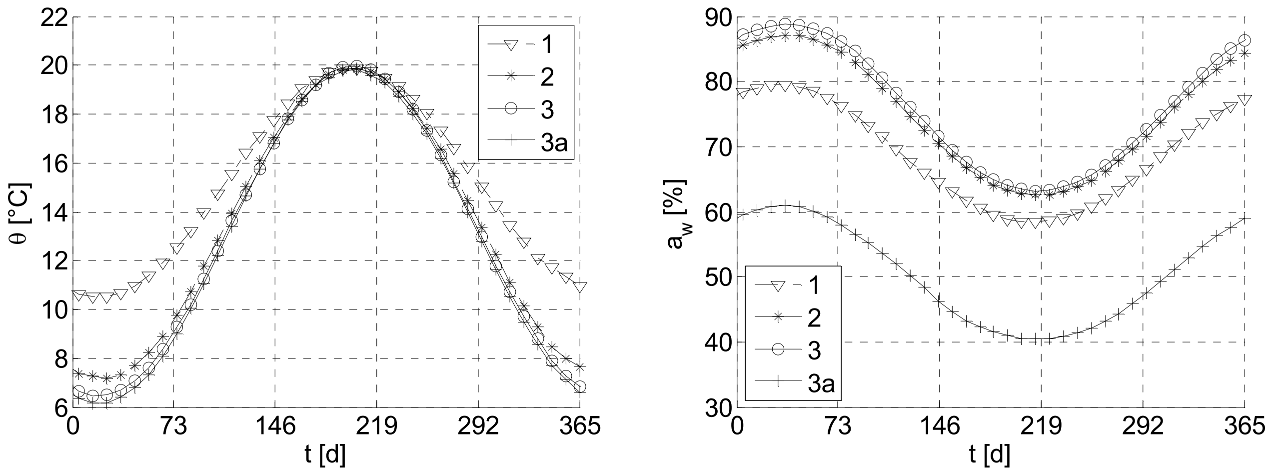

Figure 10 Temperature and water activity trends at the position presenting maximal water activity (see point Max in Figure 9) for cases 1, 2, 3 and 3a

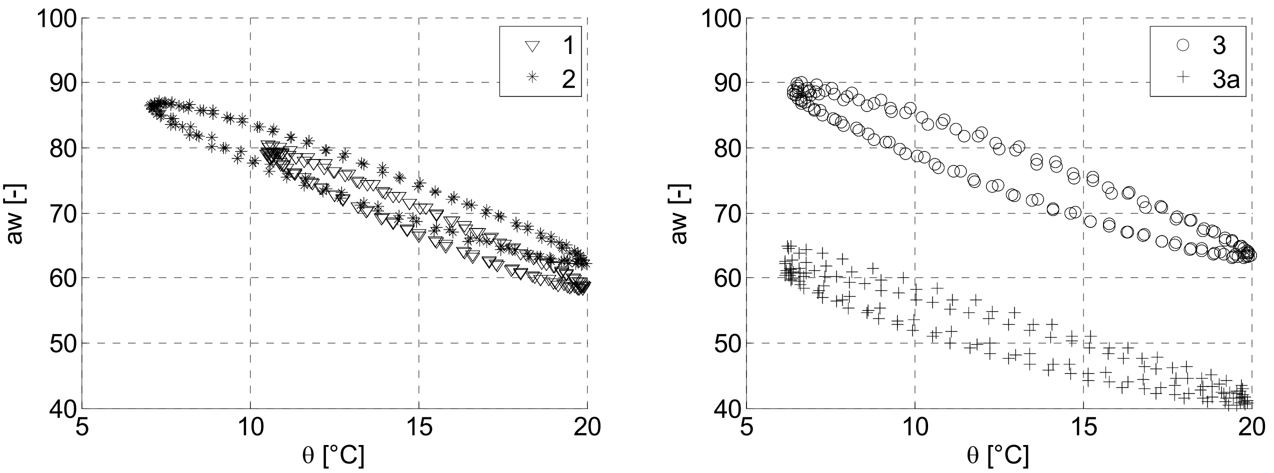

Figure 11 Yearly evolution of water activity versus temperature at the position with maximal water activity (see point Max in Figure 9) for cases 1, 2, 3 and 3a

A further aim of the simulation regards the assessment of the mold formation on the internal surface. At the corners between the ceiling and the wall (point 1 and 2, Figure 9) the highest value of relative humidity is reached so the mold growth has to be verified at these locations. The values of temperature and relative humidity are shown in Figure 12. Water activity over 70% with temperature values between 14 and 15°C are determined in correspondence of the lower corner. Even if these values are not critical for mold growth, they are close to the temperature and moisture range in which the germination can start.

Also in this case, a reduction of the internal humidity would exclude any risk, as can be observed in comparing case 3 and 3a in Figure 12.

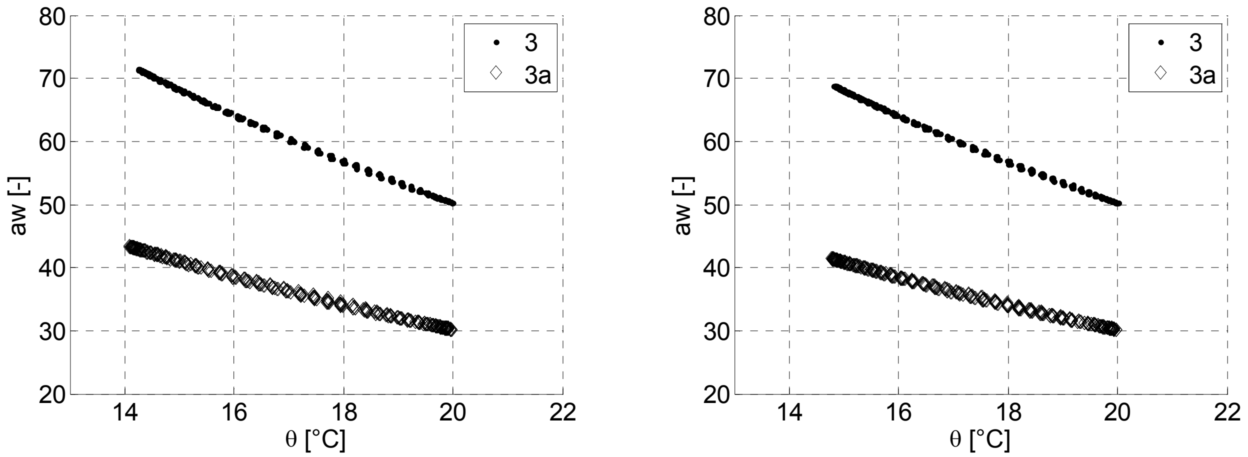

Figure 12 Yearly evolution of water activity versus temperature. Left: lower corner (position 1 in Figure 9). Right: upper corner (position 2 in Figure 9)

6. Conclusions

The simulation example presented in this work confirms the capability of COMSOL Multiphysics for solution of practical building physics problems such as the prediction of condensation formation and mold growth in constructions. The application to complex 3D geometries represents an advantage in comparison to others programs.

An experimental verification of the results will be performed within the 3ENCULT project.

Modeling of convection inside the hollow bricks will represent a further development of the model.

7. Acknowledgements

These results are part of the research, calculation and simulation work in the work package 3 of the European project 3ENCULT funded under the 7th Framework Program (number: 260162, title: Efficient Energy for EU Cultural Heritage, duration: 01.10.2010 – 31.03.2014).

8. Nomenclature

c	*[J/(kg K)]*	*Heat capacity*
D	*[m²/s]*	*Diffusivity*
Dm,φ	*[kg/(m s)]*	*Transport coefficients*
Dm,T	*[kg/(m s K)]*	
De,φ	*[W/m]*	
De,T	*[W/(m K)]*	
h	*[J/m³]*	*Enthalpy*
j	*[kg/(m²s)]*	*Mass flux*
p	*[Pa]*	*Pressure*
q	*[W/(m²)]*	*Heat flux*
R	*[J/(kg K)]*	*Gas constant*
t	*[s]*	*Time*
T	*[K]*	*Temperature*
θ	*[°C]*	*Temperature*
u	*[kg/m³]*	*Water content*
α	*[W/(m²K)]*	*Heat transfer coefficient*
β	*[s/m]*	*Mass transfer coefficient*
λ	*[W/(m K)]*	*Heat conductivity*
μ	*[-]*	*Vapor diffusion resistance*
ρ	*[kg/m³]*	*Density*
φ	*[%]*	*Relative humidity*
a_w	*[%]*	*Water activity*

Subscripts

a	*Air*
c	*Capillary*
d	*Dry*
f	*Free saturation*
p	*Constant pressure*
l	*Liquid*
s	*Saturated*
v	*Vapor*

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