

# Teaching Heat and Moisture Transport Modeling for Building Physics Engineering with COMSOL\*

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*We use the multiphysics package COMSOL for teaching heat and moisture transport modeling in the research area of building physics. It includes a description of how COMSOL works and six exercises with 2D, 3D, steady state and transient models. It is concluded that COMSOL is a very useful tool for this kind of engineering education. Especially, the abstraction level of working with partial differential equations (PDEs) has the advantage that the theory (also based on PDEs) can be relatively easily implemented in the models.*

**Keywords:** modeling; building physics; multiphysics; heat; moisture

## INTRODUCTION

BUILDING SPACES ARE SEPARATED from each other and from the outdoor climate by partitions: inside walls and the building envelope, facades, roofs, floors. The building envelope is subjected to a strongly fluctuating outdoor climate: sunshine, rain, wind, and air temperatures. The performance demands required for these structures depend on the requirements for comfort in the rooms of a building, the energy needed to realize the desired indoor climate, the air quality and air humidity of this climate, the durability, maintenance, use of materials, and the recyclability of these structures. In the past, the design of these structures was led by experience. Due to the more rigid requirements of performance and the enormous increase of new building techniques, new materials and new building shapes, reliance today on experience is often not applicable. The result may be building damage, a bad indoor climate, and an unnecessary high energy consumption. Therefore, the knowledge of heat and moisture transport through building structures and joints is increasingly important for building design. A clear illustration of this fact is the building code with its abundant regulations related to building physics. The knowledge, insight, and prediction models of building physics are indispensable for the realization of high quality buildings that satisfy the required performances [1–3]. Topics related with building physics published in previous issues of the *International Journal of Engineering Education* are provided in references [4–7].

## COMSOL MULTIPHYSICS SOFTWARE

Many scientific problems in building physics can be described by PDEs [8]. There are many software programs in which one specific PDE is solved. They are developed in order to obtain simulation results in a short time and, most often, much effort has been put into the simplicity of input of data, e.g. geometric data. A disadvantage is that they often are not very flexible when the user wants to change or combine models. Another drawback is that they act most often as black boxes. Another category of commercially available software, such as COMSOL [9] is developed specifically for solving PDEs where the user in principle can simulate any system of coupled PDEs. Practical physics/engineering problems, related with building physics [10, 11], in the area of heat transfer [12–21], moisture transport [22–29], fluid dynamics [30–39], and structural mechanics [40–43] can be solved with the software. One of the main advantages of COMSOL is that the user can focus on the model (PDE coefficients on the domain and the domain boundary) and does not have to spend much time on solving and visualization. The scientist can concentrate on the physics behind the models and the engineer can calculate details for designing purposes using validated models.

### *How COMSOL works*

COMSOL solves systems of coupled PDEs (up to 32 independent variables). The specified PDEs may be non-linear and time dependent and act on a 1D, 2D, or 3D geometry. The PDEs and boundary values can be represented by two forms. The coefficient form is as follows: the symbols provided by the COMSOL modeling guides are also used here.

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$$d_a \frac{\partial u}{\partial t} - \nabla \cdot (c \nabla u + \alpha u - \gamma) + \beta \nabla u + a u = f \quad \text{in } \Omega \quad (1a)$$

$$\underline{n} \cdot (c \nabla u + \alpha u - \gamma) + q u = g - \lambda \quad \text{on } \partial \Omega \quad (1b)$$

$$h u = r \quad \text{on } \partial \Omega \quad (1c)$$

The first equation (1a) is satisfied inside the domain  $\Omega$ , and the second (1b) (generalized Neumann boundary) and third (1c) (Dirichlet boundary) equations are both satisfied on the boundary of the domain  $\partial \Omega$ .  $\underline{n}$  is the outward unit normal and is calculated internally.  $\lambda$  is an unknown vector-valued function called the Lagrange multiplier. This multiplier is also calculated internally and will only be used in the case of mixed boundary conditions. The coefficients  $d_a$ ,  $c$ ,  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $a$ ,  $f$ ,  $g$ ,  $q$ , and  $r$  are scalars, vectors, matrices, or tensors. Their components can be functions of the space, time, and the solution  $u$ . For a steady state system in coefficient form,  $d_a = 0$ . Often  $c$  is called the diffusion coefficient,  $\alpha$  and  $\beta$  are convection coefficients,  $a$  is the absorption coefficient, and  $\gamma$  and  $f$  are source terms.

Other forms of the PDEs and boundary conditions available in COMSOL are the general and

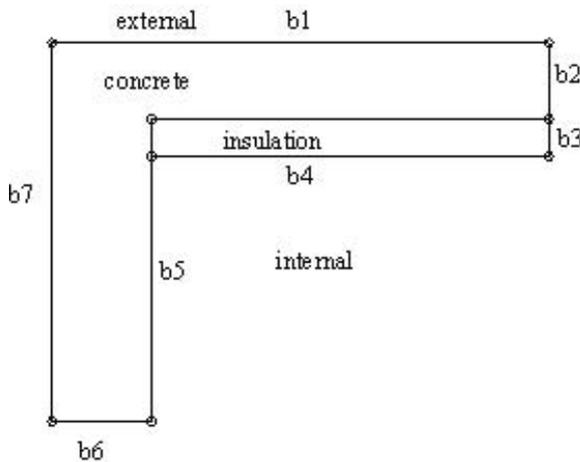


Fig. 1. Geometry of 2D thermal bridge. See Table 1 for boundary conditions specifications.

Table 1. Boundary specifications of 2D thermal bridge problem (Figure 1), where  $T$  is the temperature on the boundary and  $T_i$  and  $T_e$  are the internal and external temperatures

Boundary Segment	Boundary Type	Boundary Segment length [m]	Boundary condition [ $Wm^{-2}$ ]
b1	external	1.0	$\phi = h_{ce} * (T_e - T)$
b2	adiabatic	0.2	$\phi = 0$
b3	adiabatic	0.1	$\phi = 0$
b4	internal	0.8	$\phi = h_{ci} * (T_i - T)$
b5	internal	0.7	$\phi = h_{ci} * (T_i - T)$
b6	adiabatic	0.2	$\phi = 0$
b7	adiabatic	1.0	$\phi = 0$

weak forms. In this paper only the coefficient form is used.

*Example: COMSOL code and results of a 2D steady state thermal bridge.*

A 2D steady state thermal bridge problem is used as an example of how Comsol works. In figure 1 the geometry of the 2D thermal bridge problem is shown.

Figure 1 represents half of a horizontal section of an insulated external wall. B7 is the axis of symmetry. The internal wall, surrounded by b5, b6 en b7 intersects the insulation and forms a so-called thermal bridge.

In Table 1 the lengths and boundary conditions of each boundary segment are given.

The PDE model for the inside of the domain is given by:

$$\nabla \cdot (K \nabla T) = 0 \quad (2)$$

Where  $K$  is thermal conductivity and  $T$  is temperature. Using the coefficient form (1a) and the PDE model (2), it follows that  $u$  equals  $T$  and the coefficients of (1a) are all zero ( $a = d_a = f = \alpha = \beta = \gamma = 0$ ) except  $c$ . The  $c$  coefficient equals the heat conductivities at the sub-domains concrete ( $K_{concr}$ ) and insulation ( $K_{insul}$ ). The boundary values are heat fluxes and so the Neumann condition is applied. For example, boundary condition b1:  $\phi = h_{ce} * (T_e - T)$  is represented by taking  $q = h_{ce}$ ,  $g = h_{ce} * T_e$  in eq. (1b). Note that the term  $\underline{n} \cdot c \nabla u$  in (1b) represents the heat flow into the domain and is calculated internally, and the term  $\lambda$  in (1b) is zero because mixed boundary conditions are not applied in this example.

In COMSOL there are, generally speaking, two ways to implement problems: by user interface or by scripts. The user interface can be seen as a tool that generates scripts. In order to show how it works, Figure 2 shows the complete COMSOL script to solve the example problem. The default values of all PDE and boundary coefficients are 0. Also some comments (%) are included for better understanding of the code.

The initial mesh is presented in Figure 3, and the solution in Figure 4. Also temperature ratios and transmission coefficients can be calculated.

This example shows the transparency and flexibility of PDE models in COMSOL. The reader should notice that in this Section we focused on how COMSOL works. When introducing COMSOL for educational purposes we don't start with scripts but with the user interface (see below).

## INTRODUCING NUMERICAL EXERCISES

### How to start

The COMSOL Class kit version allows up to 30 students to work simultaneously. For exercises we assume that each student has a laptop connected

```

%CONSTANTS
hi=7.7;      %heat transfer coefficient internal
he=25;      %heat transfer coefficient external
Ti=20;      %air temperature internal
Te=-10;     %air temperature external
KCONCR=1;   %heat conductivity concrete
KINSUL=0.03; %heat conductivity insulation

%GEOMETRY: poly2(XDATA,YDATA) ; 2D polygon
CONCR=poly2([0 0 1 1 0.2 0.2],[0 1 1 0.8 0.8 0]); %concrete
INSUL=poly2([0.2 0.2 1 1],[0.7 0.8 0.8 0.7]); %insulation
fem.geom=CONCR+INSUL; %fem geometry
fem.dim=1;%fem geometry

%COEFFICIENTS OF THE PDE/Boundary problem
fem.equ.c={KCONCR KINSUL}; % fem coefficient c
fem.bnd.g={0 0 he*Te hi*Ti 0 hi*Ti 0 0 0}; % fem coefficient g
fem.bnd.q={0 0 he*Te hi 0 hi 0 0 0}; % fem coefficient q
fem.mesh=meshinit(fem); % initialize mesh
fem.xmesh=meshextend(fem); % extended mesh
fem.sol=femlin(fem); % solve, steady problem
meshplot(fem) % solve, steady problem
postplot(fem,'tridata','u','tribar','on') % plot solution

```

Fig. 2. Complete COMSOL code for solving 2D thermal bridge problem.

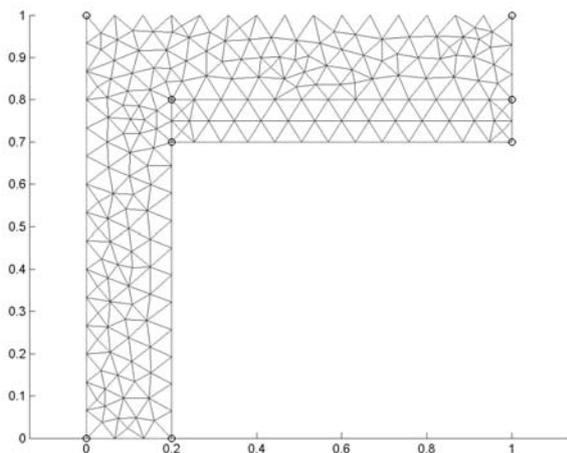


Fig. 3. The mesh of 2D thermal bridge problem.

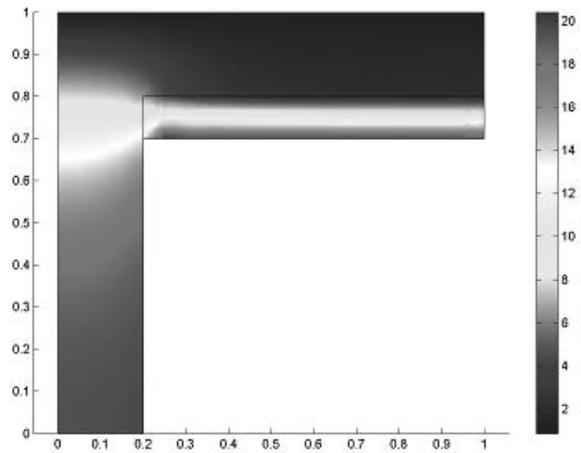


Fig. 4. Solution (temperature distribution) of 2D thermal bridge problem.

within our local network. After installing the software from a server the students are ready to start the introduction of COMSOL.

There is an overwhelming amount of literature available which can be used for introducing COMSOL to students. We refer to the website of Comsol [9] as a good starting point for finding introduction guides. Because our students have a background in building physics, they are already familiar with thermal bridges. So we introduce COMSOL by showing how the thermal bridge of Figure 1 can be simulated using a tutorial involving hands-on learning for new users. A summary of this tutorial is provided below.

After starting COMSOL the first thing the graduates have to do is select a new application mode using the Model Navigator. See Figure 5.

After this selection, the main user interface appears. See Figure 6.

The basic flow of actions is indicated by the order of the toolbar buttons and the menus. It works from left to right when defining, solving, and post-processing a model. We skip File-Edit-Options for now and proceed with **Draw**. This button is used to enter the geometry. Figure 7 shows the geometry of our typical problem to be built by the students.

After this step, the Physics has to be provided. Using the corresponding menu the PDE coefficients (i.e. heat conduction coefficient for concrete and insulation) and boundary conditions (i.e. the heat transfer coefficients and surrounding temperatures) are entered. At this point, most work has been done for this type of problem.

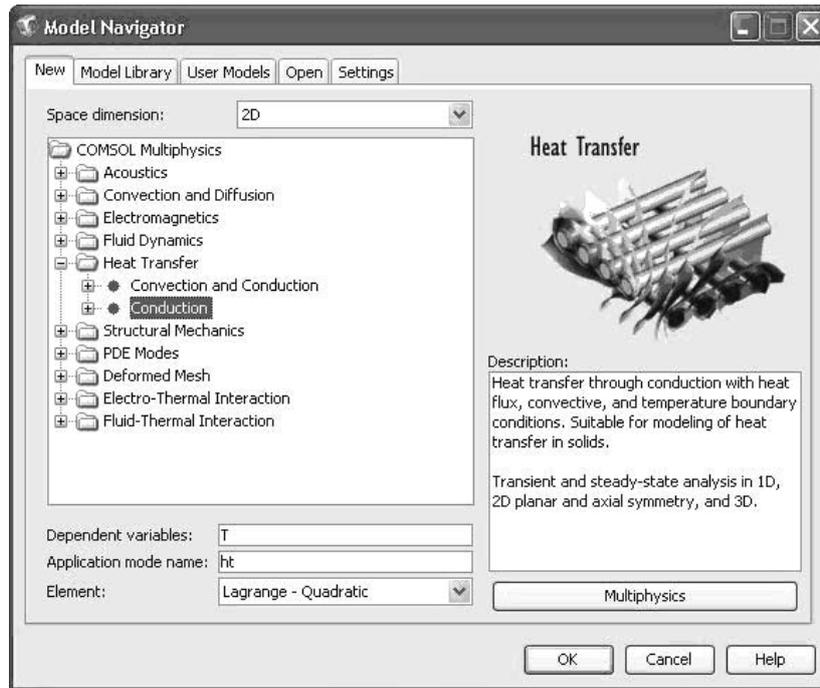


Fig. 5. Model Navigator and selecting an application suitable for modeling 2D heat transfer in solids.

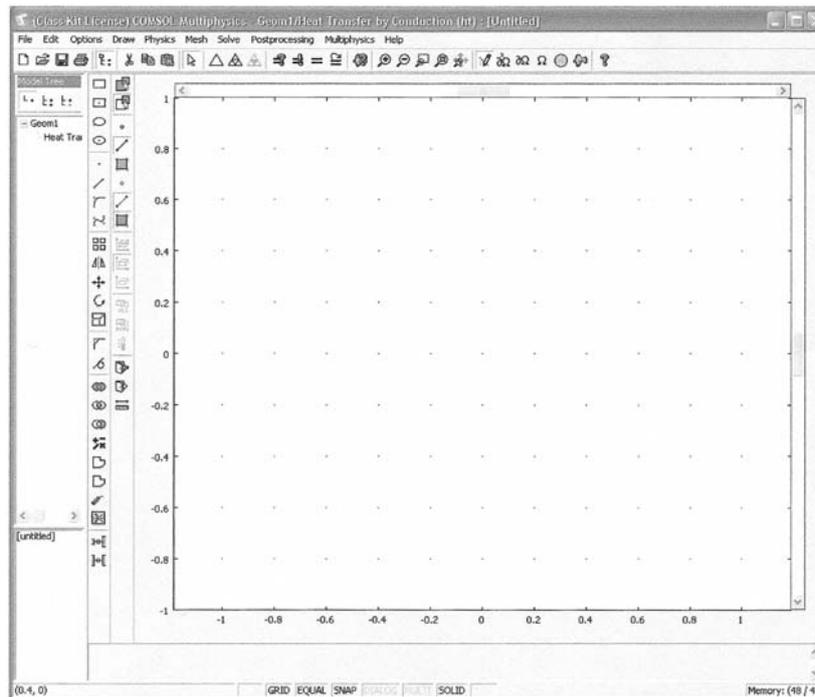


Fig. 6. Main user interface of COMSOL.

The Mesh is automatically generated by the corresponding menu, providing Figure 3. Solving (Solve) and plotting the results (Postprocessing) provides Figure 4.

This concludes the introduction of COMSOL and we proceed with the exercises. Table 2 provides a summary of the six exercises.

## STEADY STATE HEAT TRANSPORT

### Goals

The students learn:

- 1) The relation with their current knowledge of heat transport, the corresponding PDE and boundary conditions.

Table 2. Overview of the exercises

Exercise nr.	1D/2D/3D	(H)eat/ Moisture	(S)teady (S)tate/ (T)ransient
1	2D	H	SS
2	2D	H	T
3	3D	H	SST
4	2D	M	SS
5	1D	M	T
6	2D	HM	SST

- 2) What the effect is of adding (inside/outside) insulation material.
- 3) To recognize different types of thermal bridges.
- 4) To evaluate thermal constructions using the appropriate performance indicators.

#### Exercise 1

The graduates start with the modeling and simulation of a homogeneous external wall construction of concrete with a thickness of 0.20m (see Figure 8).

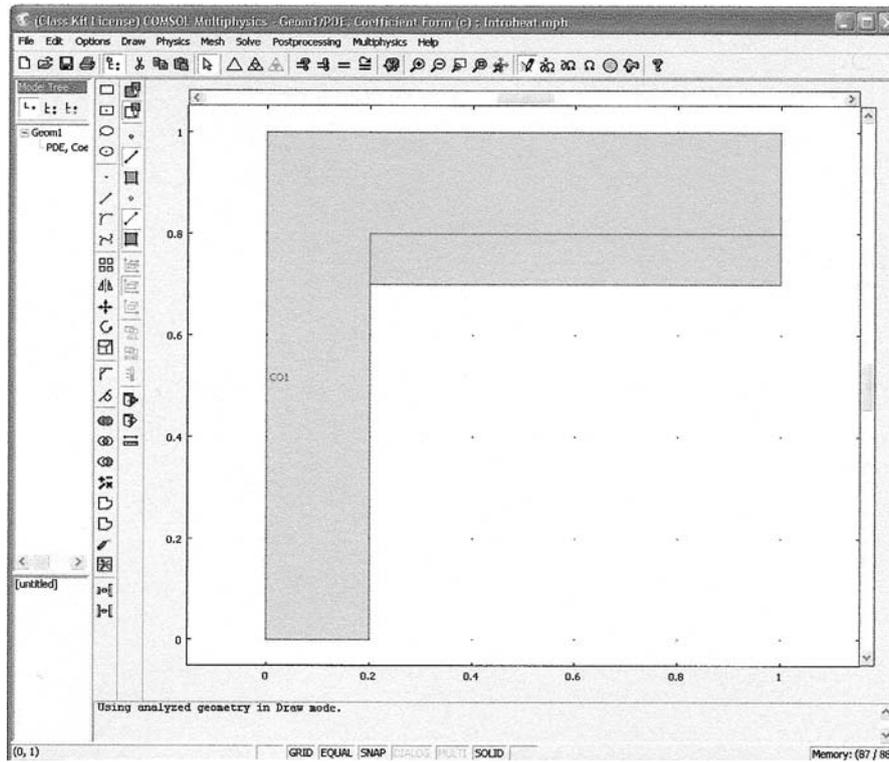


Fig. 7. Geometry to be built.

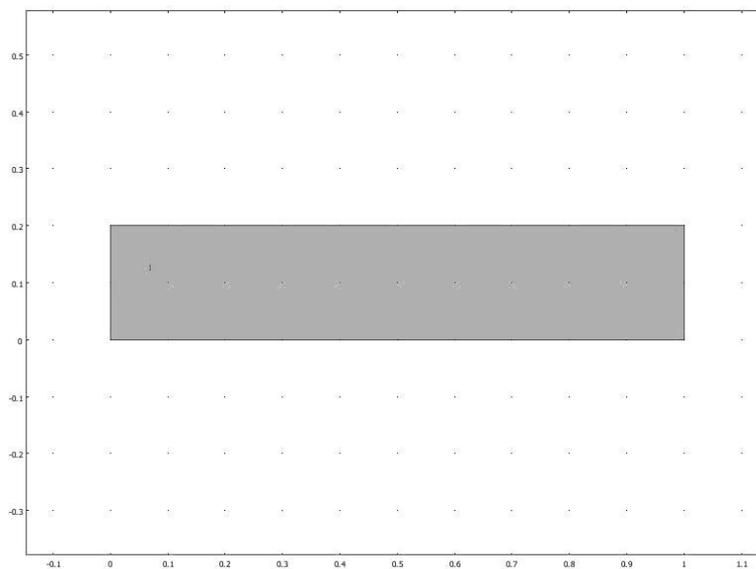


Fig. 8. A homogeneous external wall construction.

After simulation of the temperature distribution using COMSOL, the following thermal resistance network (already familiar for the students) is used for verification of the simulated surface temperatures (see Figure 9).

The graduates proceed by adding 8 cm of insulation to the outside and inside of the homogeneous wall. The surface temperatures at the outside, interface and inside surfaces, heat loss and U-value of the construction are calculated by hand and by a numerical computation. The students should notice what the effect is of insulating the external wall on the heat fluxes and surface

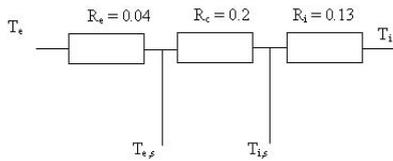


Fig. 9. Thermal resistance network. R is thermal resistance [ $m^2K/W$ ]; T is temperature [ $^{\circ}C$ ]; Indices: e, external; i, internal; c, construction, s, surface.

temperatures and the difference between outdoor and indoor insulation.

The next step is to construct a corner of the external wall. This case will change to 2D heat transfer. The students can make a subdivision in outdoor corners (largest external surface) and indoor corners.

Another example of 2D heat transfer is a thermal bridge formed by a break in the insulation material of an external wall by a well conductive material like concrete as shown in Figure 11.

Figure 12 shows a compilation of the results obtained by the students.

The following performance indicators are calculated for each thermal bridge of Figure 12: The lowest inside surface temperature, which is a measure of the condensation risk and the total heat flow per meter construction ( $W/m$ ), i.e. a measure of energy losses.

*Exercise 2*

First, the graduates will start with an estimate of the transient behavior of the external wall (see

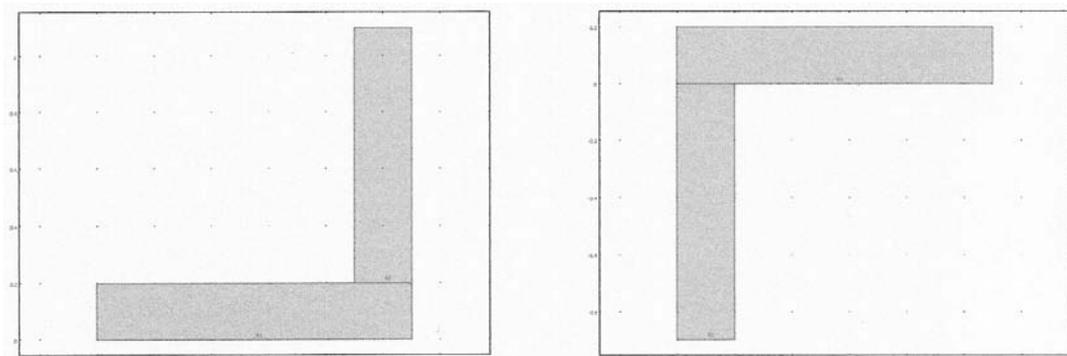


Fig. 10. Homogenous corner walls.

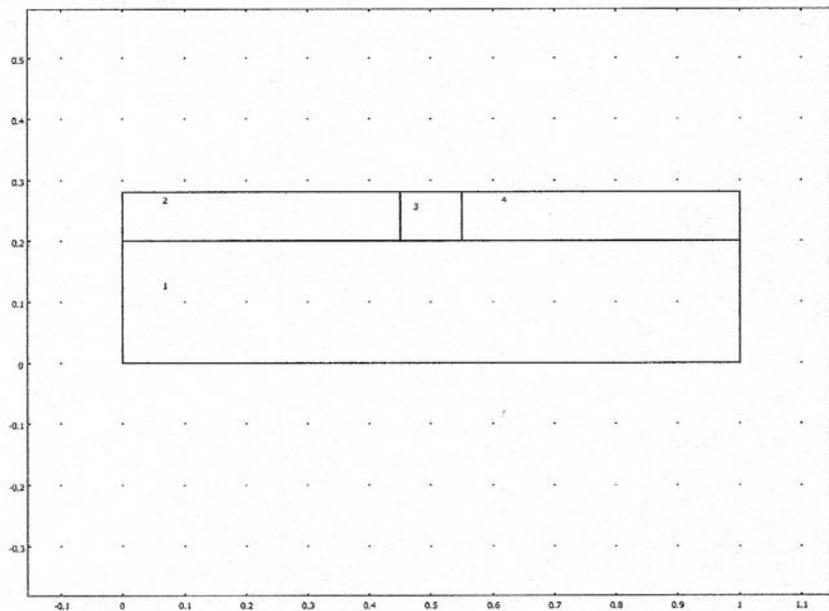


Fig. 11. Thermal bridge formed by a break in the insulation material.

Figure 12 bottom left/right) by a sine curve modeled outdoor climate using a global expression (see Figure 13).

The students will make an estimation of the transient behavior during a day and during a year. Figure 14 shows a compilation of the results obtain by the students.

The students study their animations of the

dynamic temperature distributions to estimate the penetration depths of the daily and yearly fluctuations and to show the effect of position of the insulation material on the occurring temperature differences in the concrete. The latter is important for the mechanical behavior of the concrete construction.

So far, the simulations results are not very

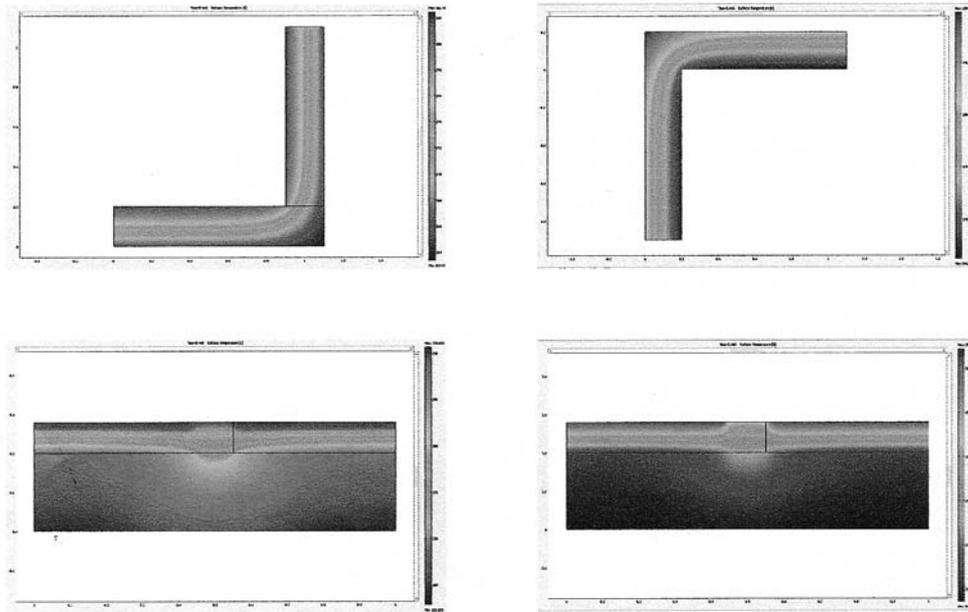


Fig. 12. Four examples of thermal bridges.

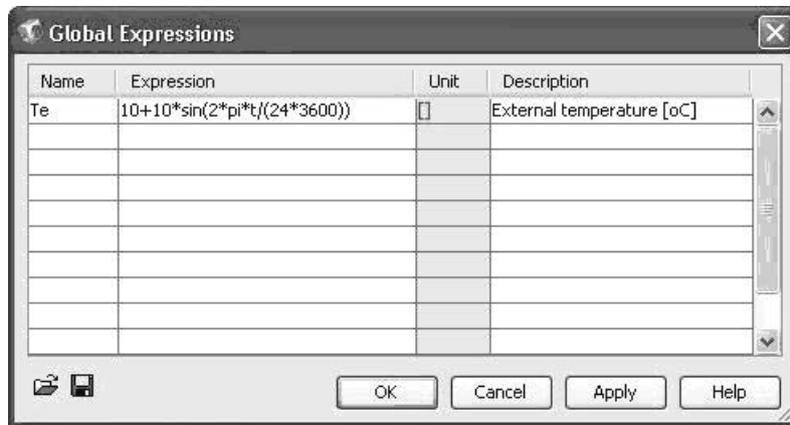


Fig. 13. A global expression.

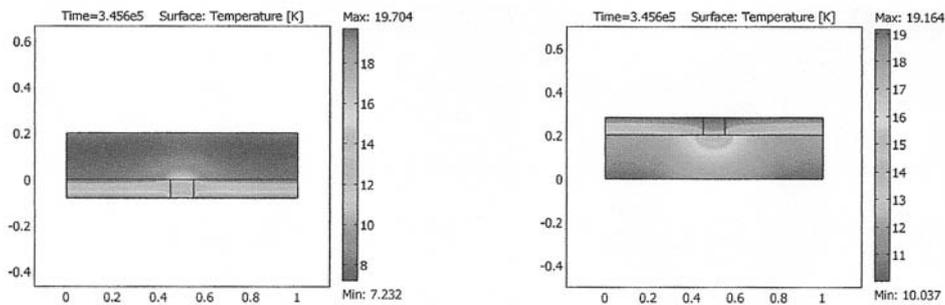


Fig. 14. Transient heat transfer in two constructions with insulation material at different sides.

realistic due to the artificial approximation of the external temperature (sinus curve). To improve this, the hourly values from a climate data file for the outdoor temperature with and without solar irradiation are added to the models. Compared with the results above, the students should conclude that real climate data are necessary.

For the dynamic case, the following performance indicators are calculated, i.e. the lowest inside surface temperature during a cold period and the total heat loss per meter construction (MJ/m) during a year.

### CASE STUDY: A STEEL BEAM PENETRATING INSIDE INSULATION 3D

#### Goals

The students learn:

- 1) To implement a 3D application from a real case from the practice
- 2) To evaluate dynamic 3D thermal results using the related performance indicators

#### Exercise 3

In the design study of the Art Gallery in Rotterdam the architect (Rem Koolhaas) made the decision to use inside insulation. The outdoor facade is formed by 250 mm concrete, also 80 mm insulation material inside, finished by gypsum board on the inside surface. Internal floor constructions were supported by steel IPE 300

Table 3. Material properties

Material	Thermal conductivity $k$ [W/m.K]	Density $\rho$ [kg/m <sup>3</sup> ]	Specific heat $c$ [J/kg.K]
Concrete	1.6	2500	840
Mineral wool	0.037	50	840
Gypsum board	0.2	850	850

beams. The steel beams form 3D thermal bridges by penetrating the inside insulation. Furthermore, the steel beams are not protected against fire. Table 3 shows the materials properties and Figure 15 presents the vertical sections of the construction.

The students calculate the (steady state) 3D thermal bridge effect of the uninsulated steel beams penetrating the insulation material. Furthermore, they use the already mentioned performance indicators but now applied to a 3D construction. They make two animations showing the most critical place during the summer and during the winter.

In actuality, it was decided that the steel beam should be insulated. The graduates were asked to make a proposal for the thickness and kind of insulation, given that the RH near the coldest surface should not exceed 70 % RH. They also needed to show that their design met this requirement. Figure 16 shows an exemplary result obtained by the students.

### STEADY STATE MOISTURE (VAPOUR) TRANSPORT

#### Goals

The students learn:

- 1) The relation with their current knowledge on vapor transport, the corresponding PDE and boundary conditions.
- 2) To implement and simulate vapor transport.
- 3) To evaluate hygric constructions using the important performance indicators.
- 4) To make use of vapor-resistant barriers to improve the situation.

#### Exercise 4

In this part, the students make a calculation of the vapor transfer through external walls. They start with 1D steady state calculations of the three types

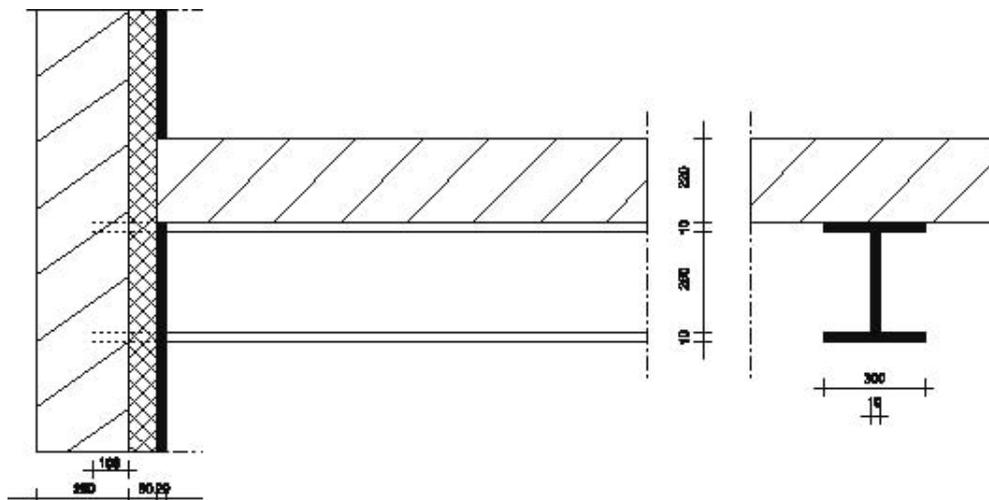


Fig. 15. Design of the construction.

of walls of the first exercise: non-insulated, internal insulated, and external insulated. They model and simulate the vapor distributions of each of three walls for a typical winter and summer situation (in total, six variants). They find out what the appropriate material properties and boundary conditions are. After plotting the vapor pressure across the cross-section of each variant, the graduates make use of the calculated temperatures across the walls from Exercise 1 to calculate the saturated vapor pressures from these section temperatures and plot

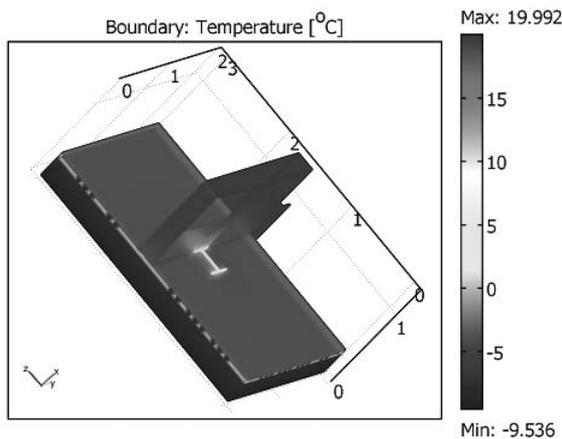


Fig. 16. Exemplary result of temperature distribution.

these values. Figure 17 shows the vapor distribution obtained by the students.

The graduates evaluate the risk for condensation in the cross-section of the walls and estimate the condensation amounts during a month. Figure 18 provides the condensation risk distribution.

The students simulate the use of vapor-resistant barriers to improve the situation in case of condensation problems. They repeat the calculations in these cases with a vapor barrier at the indoor and outdoor surfaces and formulate conclusions.

## TRANSIENT MOISTURE (LIQUID) TRANSPORT

### Goals

The students learn:

- 1) The relation with their current knowledge of liquid transport, the corresponding PDE and boundary conditions.
- 2) To implement and simulate liquid transport, including realistic material properties.
- 3) To evaluate the performance of building materials during drying and wetting.

### Exercise

The wetting and drying of concrete and sand-lime brick under isothermal conditions is considered. The students start with the following

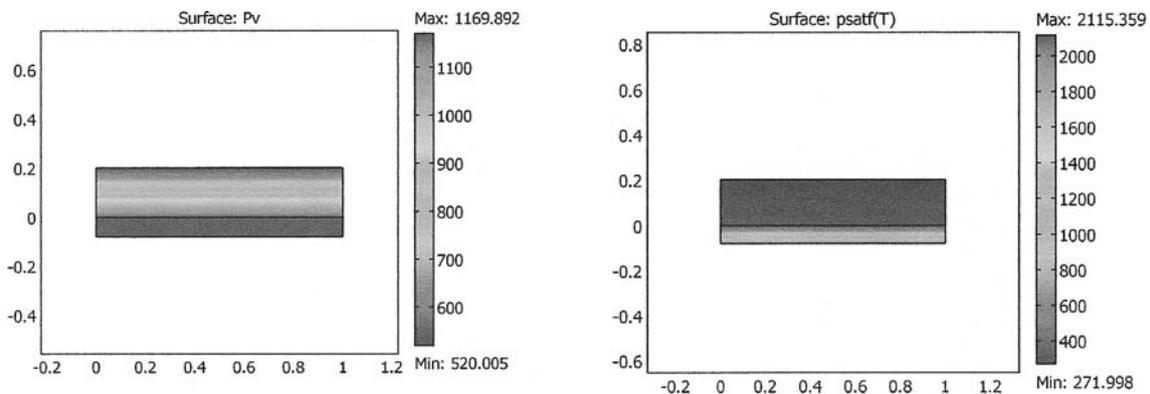


Fig. 17. Vapor distribution (left) and saturation vapor distribution (right).

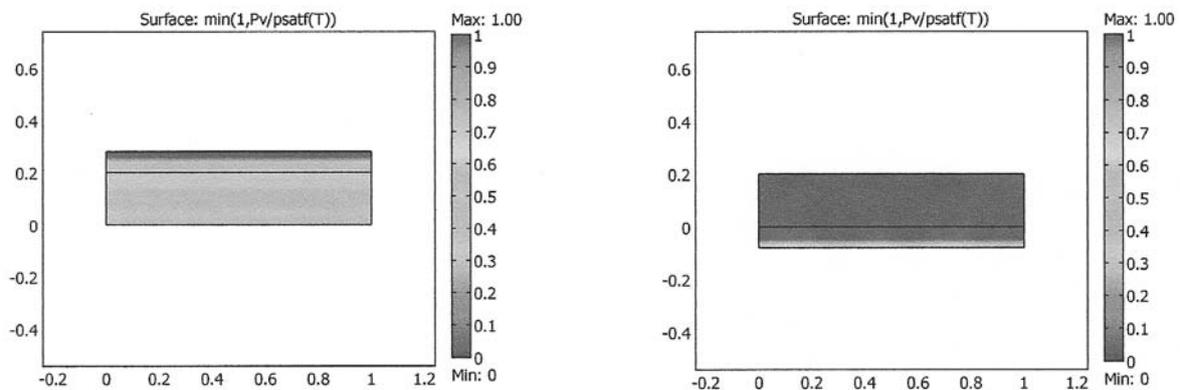


Fig. 18. Condensation risk with outside (left) and inside (right) insulation.

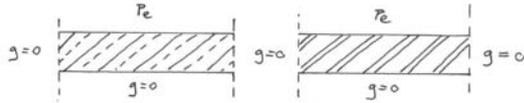


Fig. 19. Concept constructions used for studying liquid transport. Left: sand-lime brick, right: concrete.

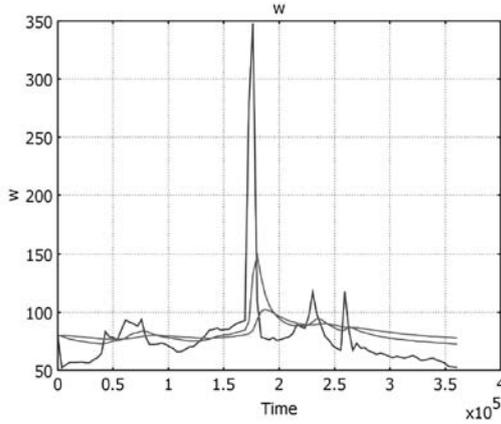


Fig. 20. Exemplary result of liquid transport. The moisture content in the concrete at the external surface (blue), 1 mm (green) and 2 mm (red) inside the material.

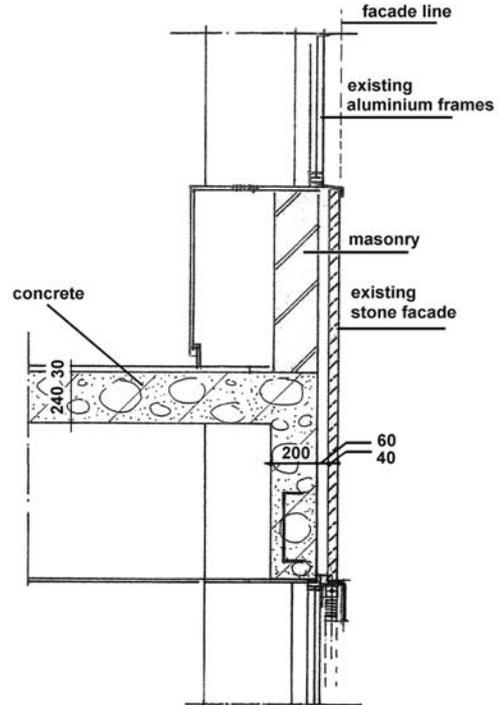


Fig. 21. Vertical section of the façade.

construction: the external blade of a vertical construction (width 0.10 m) consisting of concrete or sand-lime brick. See Figure 19.

The physical problem is that the concrete and sand-lime brick are both saturated with moisture (rain penetration) caused by a leakage during the past. The first goal is to estimate the drying times of both materials. The students calculate the drying times of both materials (concrete and sand-lime brick) using simplified material properties and steady state conditions outside. They calculate again the drying times of both materials, but now use moisture-dependent material properties and a fluctuating external vapor pressure. The second goal is to investigate whether runoff occurs during heavy rain showers for both materials. The graduates calculate the moisture content near the surface during heavy rain showers and evaluate whether runoff occurs for concrete and sand-lime brick. They use the previous model and implement a variable external climate using a file containing the external vapor pressure and precipitation. Figure 20 shows a result obtained by the students.

The graduates observe that the moisture content at the external surface exceeds the saturation moisture content of  $150 \text{ kg/m}^3$  and conclude that rain driven runoff has occurred.

### CASE STUDY: HYGRO THERMAL DESIGN OF BUILDING FACADE (2D)

#### Goal

The students learn to apply the main heat and moisture modeling skills for a real case.

Table 4. Thermal and hygric properties of the building materials

Material	Thermal conductivity kK [W/(m.K)]	Density $\rho$ [kg/m <sup>3</sup> ]	Diffusion resistance $\mu$ [-]
Brick	0.6	1900	10
Natural stone	2.3	2440	140
PUR	0.035	33	50
Concrete	1.6	2300	180
Mineral wool	0.040	60	1.3
XPS	0.034	30	100

#### Exercise 6

The students start by studying a paper on the design of the façade of an office building [44]. The design is presented in Figure 21 and the material properties are provided in Table 4.

The first step is to reproduce some results of the paper. While using COMSOL, the graduates simulate the minimal surface temperature at the inside of the construction (see Figure 22) using an equivalent heat conduction coefficient for the cavity.

The next step is to simulate two more variants: polyurethane (PUR) in the cavity and extruded polystyrene (XPS) at the inside surface. All three steady state models will be extended step-by-step to transient heat and moisture transfer models.

#### Thermal transient

The students simulate again the minimal surface temperature at the inside of the construction for the three variants. The simulation is now transient by using an external climate file containing hourly values for the air temperature and solar radiation

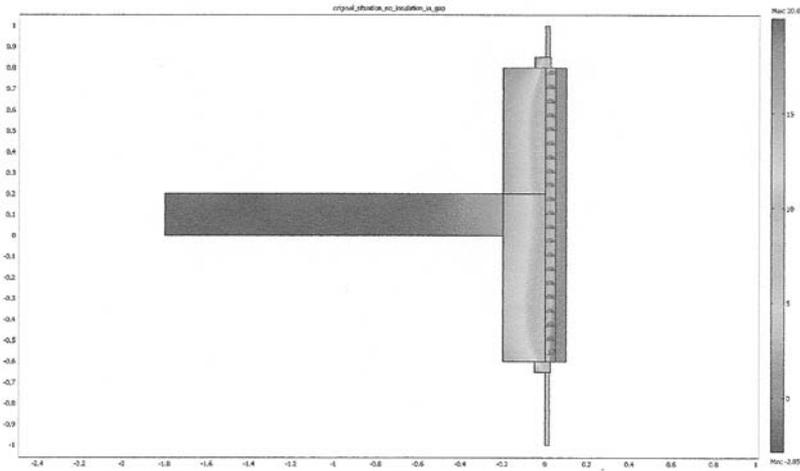


Fig. 22. Steady state temperature distribution of the façade.

and a steady indoor climate. They use the climate files of previous exercises.

*Adding moisture (hygric)*

The next step is to model vapor transport (Hygric, steady state). The students simulate similar to part 1, the vapor pressure distribution and calculate the maximum vapor pressure at the inside surface of the construction for the three variants.

*Hygric, transient*

The graduates simulate again the maximum vapor pressure at the inside of the construction for the three variants but now transient using an external climate file containing hourly values for

the vapor pressure and a steady indoor climate. The last step of this case study is to develop a combined model for heat and vapor transport.

*Thermal—hygric, steady state*

The students simulate the relative humidity distribution (RH) and calculate the maximum RH at the inside surface of the construction for the three variants.

*Thermal—hygric, transient*

They simulate again the maximum RH at the inside of the construction for the three variants but now transient using an external climate file and a

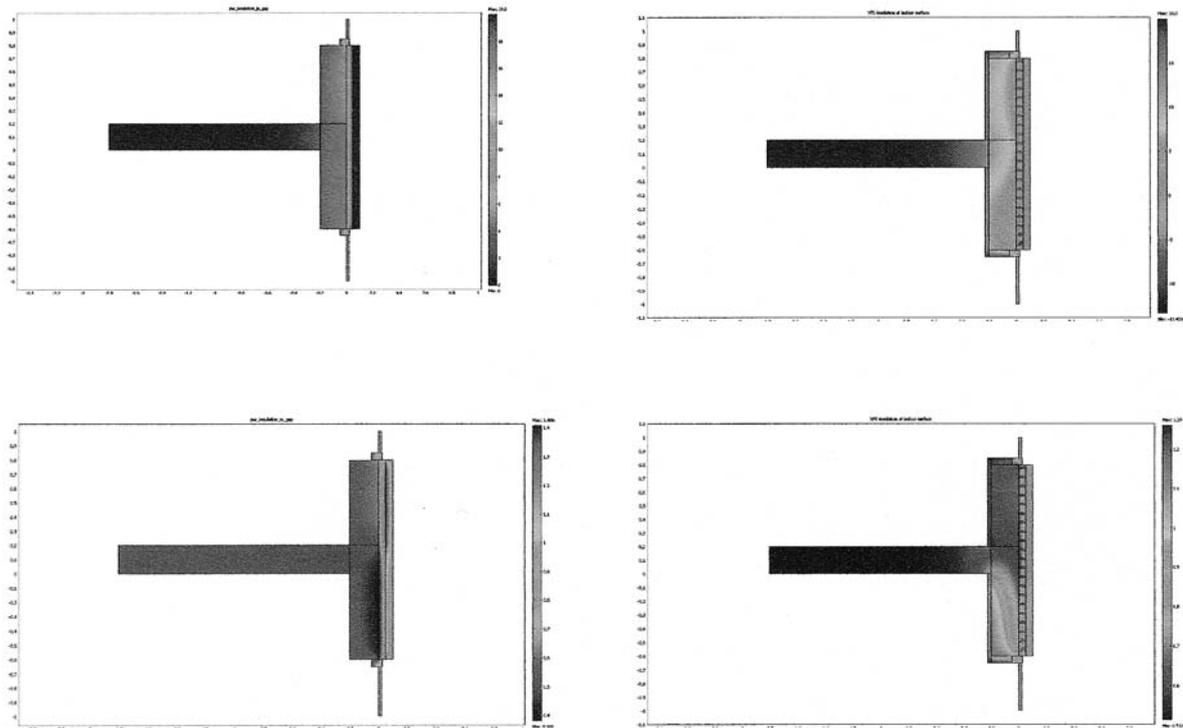


Fig. 23. Left: Using PUR in the cavity, top: temperature distribution; bottom: relative humidity. Right: Similar using XPS.

steady indoor climate and use the climate files of previous exercises.

Figure 23 shows exemplary results obtained by the students.

In this exercise, the students conclude that the insulation retrofitting of a facade with a natural stone slab has important building physical effects. Thermal and hygric simulations show that the occurrence of condensing moisture at the slab surface in the gap depends on the choice of insulation material and the place it is installed. Furthermore, this case study shows the potential of multiphysics modeling capabilities of COMSOL. Most of the commercial building physical simulation tools do not include this kind of complex interactions.

## CONCLUSIONS

It is concluded that the multiphysics package

COMSOL is very useful for teaching heat and moisture transport modeling in the research area of building physics. The main advantages are:

- Abstraction level. The theory based on PDEs can be relative easily implemented in the models.
- Solving capabilities. Most of the time the quality of the solution of the PDE problem is acceptable using the default settings.
- User interface. The students appreciated the presence of an intuitive user interface, especially when modeling 3D problems.
- Graphical output. The visualization tools provide a good opportunity to critically evaluate the simulation results.

It is possible to make complicated models and produce simulations within a short time, even by non experienced software users.

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