The Use of COMSOL in Teaching Heat and Moisture Transport Modeling in Building Constructions

A.W.M. van Schijndel* and H.L. Schellen
Eindhoven University of Technology, Department of Architecture, Building and Planning, Netherlands,
*P.O. Box 513 5600 MB Eindhoven, Netherlands; A.W.M.v.Schijndel@bwk.tue.nl

Abstract: This paper presents the use of the multiphysics package COMSOL for teaching heat and moisture transport modeling in the research area of building physics. It includes a description on 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 relative easily implemented in the models.

Keywords: Modeling, Building Physics, Multiphysics, Heat, Moisture, Education

1. 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 lead by experience. Due to the more rigid requirements on performance and the enormous increase of new building techniques, new materials and new building shapes this reliance on experience is often not applicable any more. 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].

2. Steady state heat transport

The students learn:
1. The relation with their current knowledge on heat transport, the corresponding PDE and boundary conditions.
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.

(1) The graduates start with the modeling and simulation of a homogeneous external wall construction of concrete with a thickness of 0.20m.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:
(2) The graduates proceed with adding 8 cm of insulation at respectively 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 temperatures and the difference between outdoor and indoor insulation.
(3) The students proceed with constructing 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.

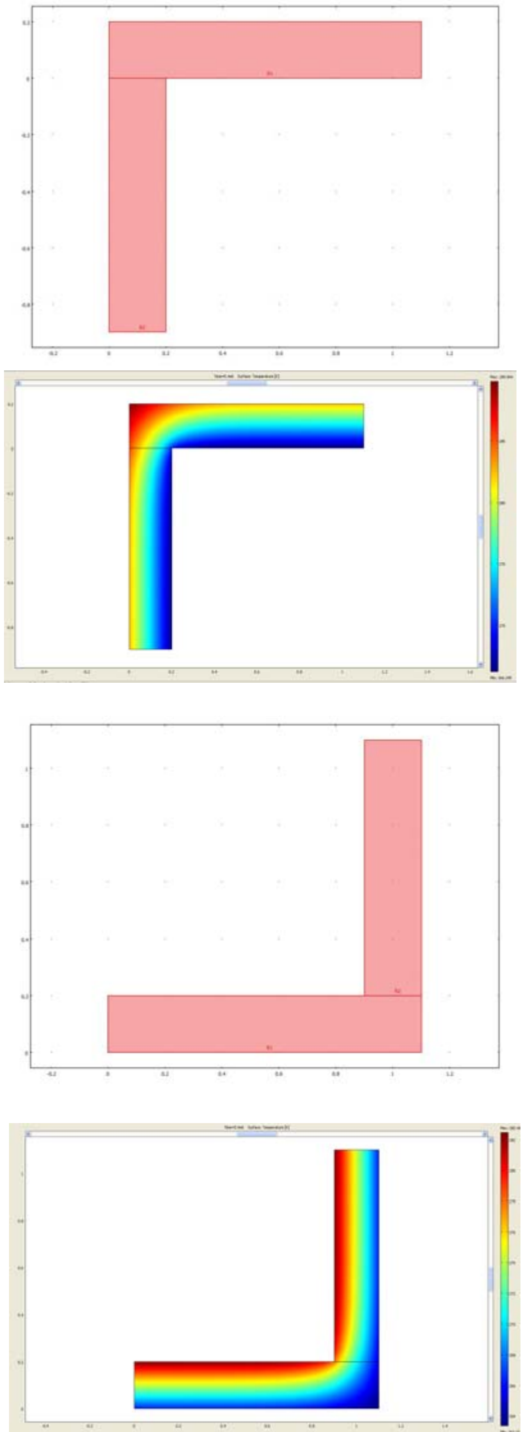


Figure 1. Homogenous corner walls

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 2.

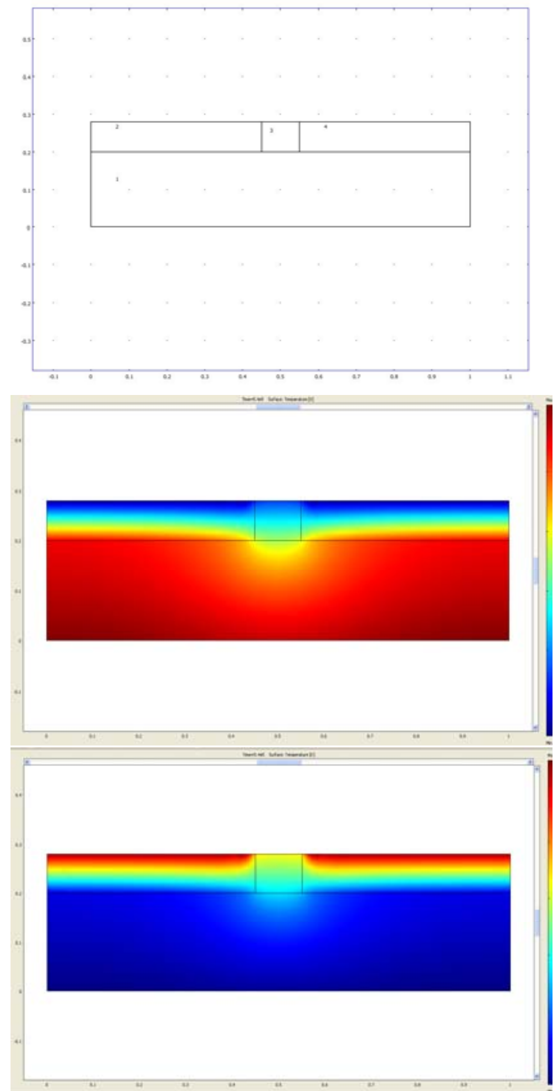


Figure 2. Thermal bridge formed by a break in the insulation material

(4) The following performance indicators are calculated for each thermal bridge of figure 2: The lowest inside surface temperature, which is a measure for the condensation risk and the total heat flow per meter construction (W/m), which is a measure for energy losses.

3. Transient heat transport

The students learn:
1. What the effect is of entering dynamics into the equation.
2. What the effect is of daily and yearly fluctuations and using real climate data.
3. To evaluate dynamic thermal results using performance indicators

(1&2) First, the graduates will start with an estimate of the transient behavior of the external wall (see figure 2) by a sine curve modeled outdoor climate using a global expression:

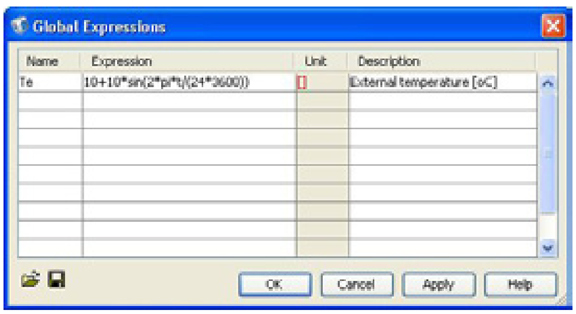
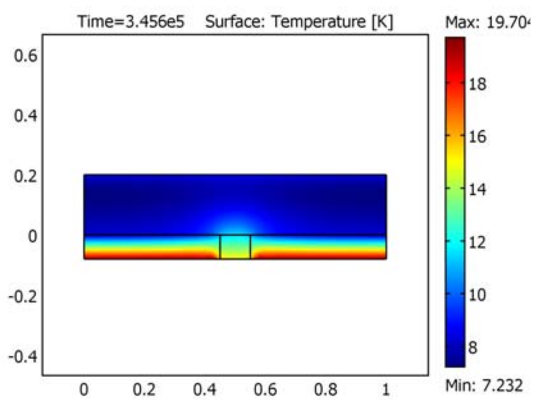


Figure 3. A global expression

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



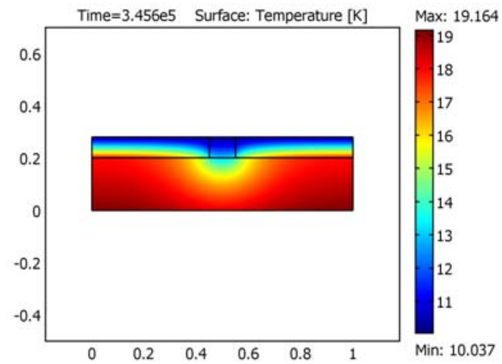


Figure 4. Transient heat transfer in two constructions with insulation material at different sides.

The students study their produced 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 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 implemented into the models. Comparing with the results above, the students should conclude that real climate data are necessary.

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

4. Case study: A steel beam penetrating inside insulation 3D

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

(1&2) 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 at the outside, 80 mm insulation material at the inside, finished by gypsum board at the inside surface. The internal floor constructions were supported by steel IPE 300 beams. The steel beams are forming 3D thermal bridges by penetrating the inside insulation. Furthermore the steel beams are not protected against fire. Table I shows the materials properties and Figure 5 presents the vertical sections of the construction.

Table I. Material properties

Material	***thermal conductivity k [W/m.K]***	***density ρ [kg/m³]***	specific heat c [J/kg.K]
Concrete	**1.6**	**2500**	**840**
Mineral wool	**0.037**	**50**	**840**
Gypsum board	**0.2**	**850**	**850**

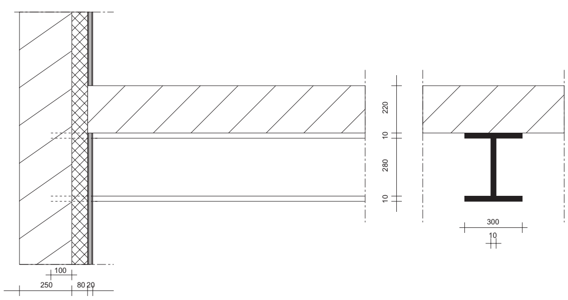


Figure 5. The design of the construction.

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 the real case, it was decided that the steel beam should be insulated. The graduates are asked to make a proposal for the thickness and kind of insulation under the condition that the RH near the coldest surface should not exceed 70 %RH. Furthermore they need to show that their design meets this requirement. Figure 6 shows an exemplary result obtained by the students:

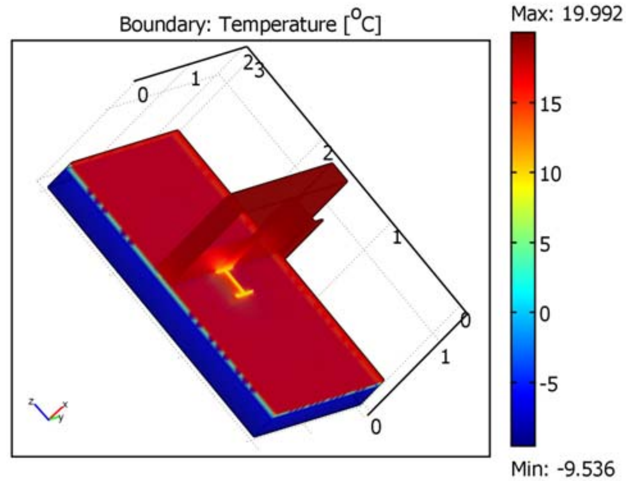


Figure 6. Exemplary result of the temperature distribution

5. Steady state moisture (vapour) transport

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

(1&2) In this part, the students will make a calculation of the vapor transfer through external walls. The graduates start with 1D steady state calculations of the three types of walls of the first exercise: non insulated wall, internal insulated and external insulated wall. The students model and simulate the vapor distributions of each of three walls for a typical winter and summer situation (thus 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 these values. Figure 7 shows the vapour distribution obtained by the students

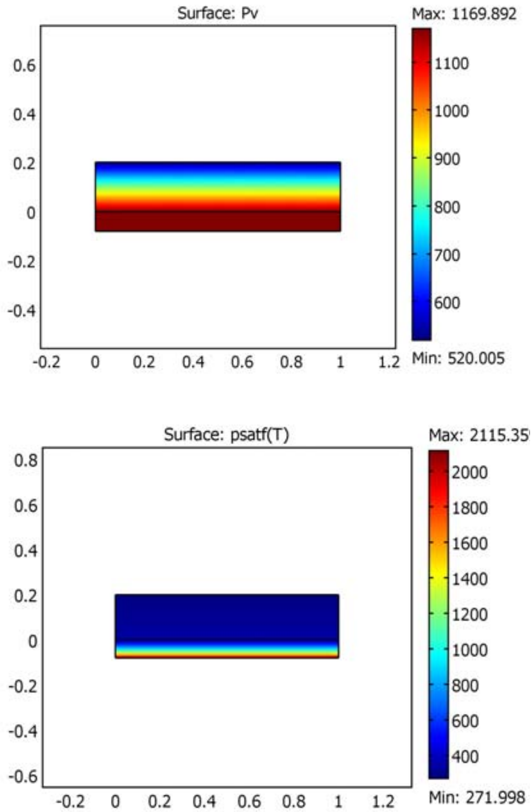


Figure 7. Vapour distribution (top) and saturation vapour distribution (bottom)

(3) The graduates evaluate the risk for condensation in the cross section of the walls and estimate the condensation amounts during a month. Figure 8 provides the condensation risk distribution.

(4) The students simulate the use of vapor resistant barriers to improve the situation above 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.

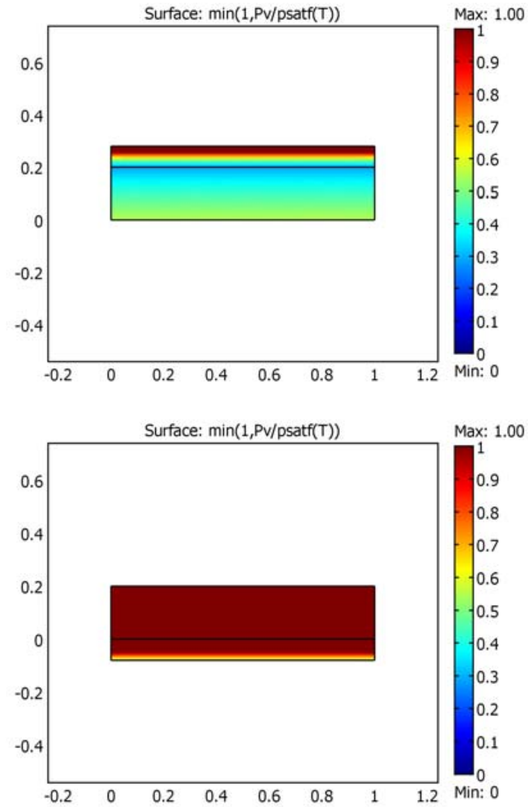


Figure 8. Condensation risk with outside (top) and inside (bottom) insulation

6. Transient moisture (Liquid) transport

The students learn:
1. The relation with their current knowledge on 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

(1&2&3) The wetting and drying of concrete and sand-lime brick under isothermal conditions is considered. The students start with the following construction: The external blade of a vertical construction (width 0.10 m) consisting of concrete or sand-lime brick. See figure 9.

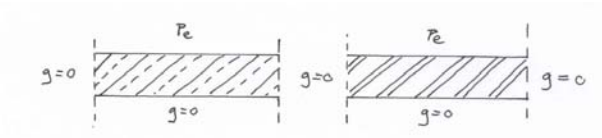


Figure 9. The concept constructions used for studying liquid transport. Left: sand-lime brick, right: concrete.

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 vapour 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 vapour pressure and precipitation.
Figure 10 shows an exemplary result obtained by the students

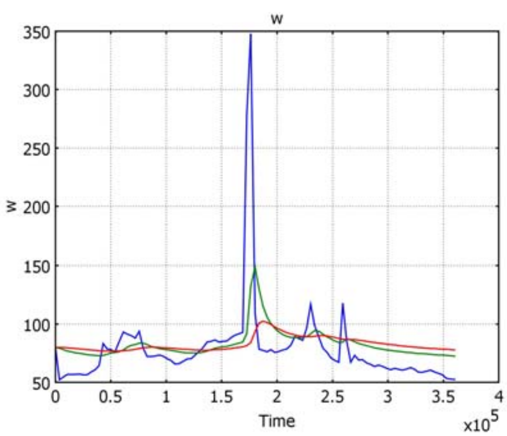


Figure 10. Exemplary result of liquid transport. The moisture content in the concrete at the external surface (blue), 1 mm (green) and 2 mm (red) inside the material.

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

7. Case study: Hygro thermal design of building facade (2D)

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

The students start with studying a paper on the design of the façade of an office building [4]. The design is presented in figure 11 and the material properties are provided in Table II.

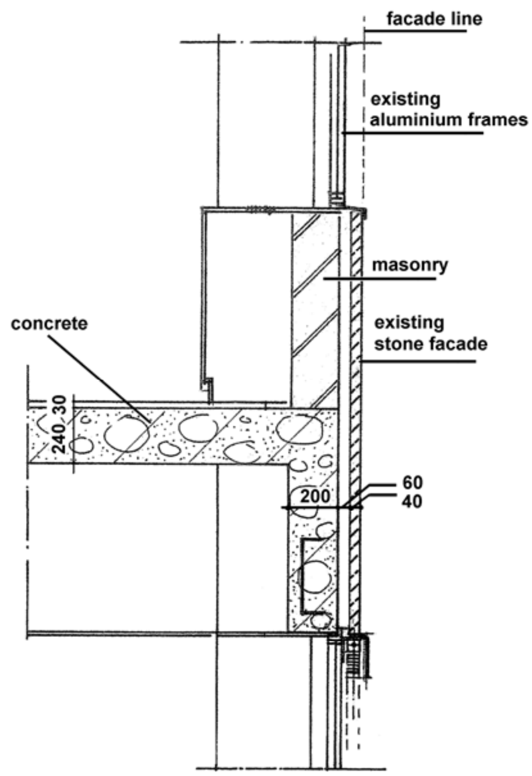


Figure 11. The vertical section of the façade.

Table II. Thermal and hygric properties of the building materials

Material	Thermal conductivity. K [W/(m·K)]	Density ρ [kg/m^3]	Diffusion resistance μ [-]
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

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 11) using an equivalent heat conduction coefficient for the cavity.

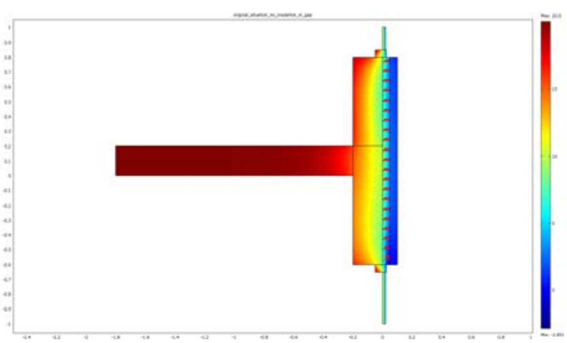


Figure 12. An exemplary result: The steady state temperature distribution of the façade.

The next step is to simulate two more variants: polyurethane (PUR) in the cavity and extruded polystryrene (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 and a steady indoor climate. They use the climate files of previous exercises.

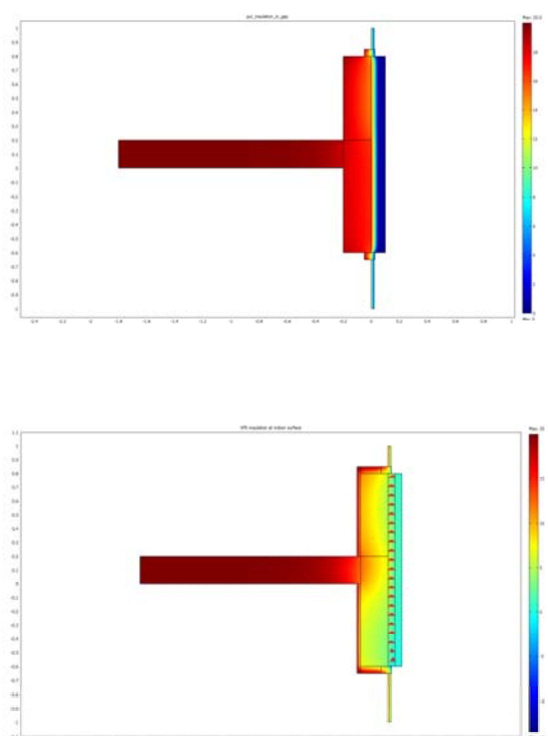
Adding moisture (hygric) - The following step is to model vapor transport (Hygric, steady state). The students simulate similar to part 1, the vapor pressure distribution and calculate the maximum vapor pressure at the inside surface of the construction for the three variants.

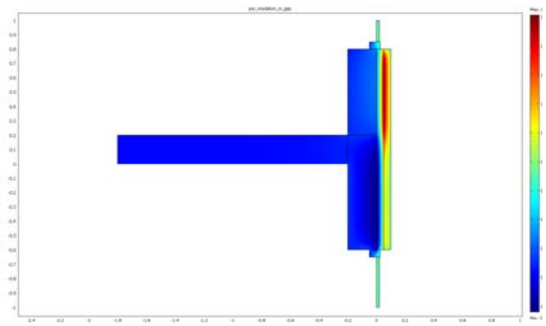
Hygric, transient – The graduates simulate again the maximum vapor pressure at the inside of the construction for the three variants but now transient using an external climate file containing hourly values for the vapor pressure and a steady indoor climate. The last step of this case study is to develop 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 steady indoor climate and use the climate files of previous exercises.

Figure 13 shows exemplary results obtained by the students.





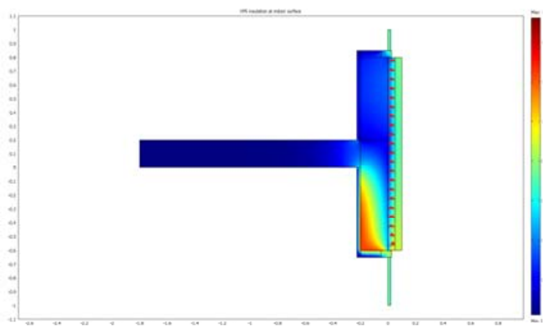


Figure 13. Exemplary results. First: Using PUR in the cavity, Second: temperature distribution; Third: relative humidity. Fourth: Similar using XPS.

For this exercise, the students should 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.

8. 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.

All together it is possible to make complicated models and produce simulations results within a short time also for non experienced software users.

References

1. M.H. de Wit, Heat and moisture in Building Envelopes, *Lecture notes*, 200 pages (2007), available at http://sts.bwk.tue.nl/7s532/

2. A.W.M. van Schijndel, Modeling and solving building physics problems with FemLab, *Building and Environment 38*, pp 319-327 (2003)

3. A.W.M. van Schijndel, Integrated Heat Air and Moisture Modeling and Simulation, PhD thesis, Eindhoven University of Technology, *ISBN90-6814-604-1*, 200 pages (2007)

4. H. L. Schellen, A.W.M. van Schijndel, The use of COMSOL to solve hygro thermal building physical problems related to insulating high rise building facades. Proceedings of the COMSOL Users Conference 2007 Grenoble, 7pages