Heat and Moisture
In
Building Envelopes

Numerical Exercises

using
MultiPhysics package
COMSOL

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http://sts.bwk.tue.nl/7s532/
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Guidelines for the report

The structure of the report is as follows:

1. **Cover**
   1.1. Title
   1.2. Date
   1.3. Authors
   1.4. Group number

2. **Goal of the exercise(s)**
   (For example ‘understanding of ...’; ‘simulating a ...’; ‘designing a …’)

3. **Theory**
   (Description of the required theory, PDEs, boundary conditions, etc.)

4. **Modeling**
   (Description of the model and solving techniques)

5. **Results**
   (Description of the (simulation) results)

6. **Calculations**
   (Description of the additional calculations (by hand))

7. **Discussion**
   (Critical evaluation of all results)

8. **Conclusion**

(Appendices)
Exercise 0:  How to start?

The multiphysics software COMSOL is used at all exercises.

0.1  Install Comsol Class kit on your computer. See Appendix A for details.

0.2  Start the Tutorial of Appendix B involving hands-on learning for new users of COMSOL

After completing these two tasks you are ready for the other exercises.
Exercise 1: Stationary heat transport

1.1 Homogeneous external wall
We start with the modeling and simulation of a homogeneous external wall construction with a thickness of 0.20m:

The boundary conditions are:

<table>
<thead>
<tr>
<th>Boundary</th>
<th>1, 4</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Thermal insulation</td>
<td>Heat flux</td>
<td>Heat flux</td>
</tr>
<tr>
<td>Heat transfer coefficient (h)</td>
<td>0</td>
<td>hi</td>
<td>he</td>
</tr>
<tr>
<td>External temperature (Tinf)</td>
<td>0</td>
<td>Ti</td>
<td>Te</td>
</tr>
</tbody>
</table>
The parameters are:

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kconcr</td>
<td>1</td>
<td>Concrete heat conduction coefficient [W/mK]</td>
</tr>
<tr>
<td>Kinsul</td>
<td>0.04</td>
<td>Insulation heat conduction coefficient [W/mK]</td>
</tr>
<tr>
<td>hi</td>
<td>7.7</td>
<td>Internal surface heat transfer coefficient [W/m²K]</td>
</tr>
<tr>
<td>he</td>
<td>25</td>
<td>External surface heat transfer coefficient [W/m²K]</td>
</tr>
<tr>
<td>Ti</td>
<td>20</td>
<td>Inside temperature [°C]</td>
</tr>
<tr>
<td>Te</td>
<td>-10</td>
<td>Outside temperature [°C]</td>
</tr>
</tbody>
</table>

1.1.1 Calculate the surface temperatures at the outside and inside surfaces of the construction by hand and by a numerical computation.

1.1.2 Calculate the heat loss and U-value of the construction by hand and compare both with your numerical results.

1.1.3 Plot the isotherms and the heat flux curves.

1.1.4 Is this really a 2D problem?

1.2. The effect of insulation

We proceed with adding 8 cm of insulation (Kinsul) at respectively the top and bottom of the homogeneous wall.

1.2.1 Calculate the surface temperatures at the outside, interface and inside surfaces of the construction by hand and by a numerical computation.

1.2.2 Calculate the heat loss and U-value of the construction by hand and compare both with your numerical results.

1.2.3 What is the effect of insulating the external wall on the heat fluxes and surface temperatures?

1.2.4 What is the difference between outdoor and indoor insulation.

1.2.5 What is your conclusion on the change of the location of the isotherms?
1.3. Corner effect
We proceed with constructing a corner of the external wall from exercise 1. This case will change to 2D heat transfer. We can make a subdivision in outdoor corners (largest external surface) and indoor corners.

1.3.1 Plot the 2D isotherms and heat flux curves for each corner type.

1.3.2 Explain the difference in calculated heat fluxes and surface temperatures for both cases.

1.3.3 Calculate the temperature ratio from both results.
1.4.4 Thermal bridge

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.

<table>
<thead>
<tr>
<th>Subdomain</th>
<th>1, 3</th>
<th>2, 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (k)</td>
<td>$K_{\text{concr}}$</td>
<td>$K_{\text{insul}}$</td>
</tr>
</tbody>
</table>

1.4.1 Plot the 2D isotherms and heat flux curves for this type of thermal bridge.

1.4.2 What is the effect of the thermal bridge on the internal and external surface temperatures compared to the 1D case of Section 1.2?

1.4.3 Make a calculation of the temperature ratio from the results.

1.4.4 Is it possible to make a calculation of the temperature ratio directly?

1.4.5 What is the effect on the calculated heat transfer compared to the 1D case of Section 1.2?

1.4.6 What is the linear U-value of the thermal bridge?

If you completed this exercise, present your results (informal) to the lecturer in order to get an approval.
Exercise 2: Transient heat transport

2.1 Daily fluctuations using a sine curve

In this part we will make use of a transient calculation. First we will start with an estimate of the transient behavior of the external wall by a sine curve modeled outdoor climate. We will make an estimation of the transient behavior during a day and during a year.

Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>thermal conductivity $k$ [W/m.K]</th>
<th>density $\rho$ [kg/m$^3$]</th>
<th>specific heat $c$ [J/kg.K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>1</td>
<td>2500</td>
<td>840</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.04</td>
<td>50</td>
<td>840</td>
</tr>
</tbody>
</table>

The daily outdoor temperature fluctuation is modeled by the following equation:

$$T_e = 10 + 10 \cdot \sin\left(\frac{2 \cdot \pi \cdot t}{24 \cdot 3600}\right)$$  \hspace{1cm} (1)

2.1.1 Simulate the dynamic temperature distribution for three types of external walls of Sections 1.1 and 1.2: non insulated wall, internal insulated and external insulated wall. Tip: Start with the stationary COMSOL models of the previous exercise and use a global expression for $T_e$. 

![Global Expressions](image.png)
2.1.2 What are the differences between the two insulated walls in relation with the total heat transfer and temperature distributions?

2.1.3 What is the effect of the position of the insulation on the mechanical behavior of the concrete construction?

2.1.4 What is the penetration depth of the daily fluctuation for the non insulated wall?

2.2 Yearly fluctuations using a sine curve
Perform the same calculations for the yearly changing outdoor temperature:

\[ T_e = 10 + 10 \cdot \sin \left( \frac{2 \cdot \pi \cdot t}{365 \cdot 24 \cdot 3600} \right) \]  \hspace{1cm} (2)

2.2.1 Simulate the dynamic temperature distribution for three types of external walls.

2.2.2 What are the differences between the two insulated walls in relation with the total heat transfer and temperature distribution?

2.2.3 What is the effect of the position of the insulation on the mechanical behavior of the concrete construction?

2.2.4 What is the penetration depth of the daily fluctuation for the non insulated wall?

2.3 Real climate data

2.3.1 Use the hourly values from a climate data file for the outdoor temperature. Compare the results and the conclusions with the results above.

2.3.2 Implement solar irradiation into your model and compare again.

If you completed this exercise, present your results (informal) to the lecturer in order to get an approval.
Exercise 3: Case 1 A steel beam penetrating inside insulation (3D)

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.

Material properties

<table>
<thead>
<tr>
<th>Material</th>
<th>thermal conductivity $k$ [W/m.K]</th>
<th>density $\rho$ [kg/m$^3$]</th>
<th>specific heat $c$ [J/kg.K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>1.6</td>
<td>2500</td>
<td>840</td>
</tr>
<tr>
<td>Mineral wool</td>
<td>0.037</td>
<td>50</td>
<td>840</td>
</tr>
<tr>
<td>Gypsum board</td>
<td>0.2</td>
<td>850</td>
<td>850</td>
</tr>
</tbody>
</table>

Design:
The parameters are:

<table>
<thead>
<tr>
<th>Name</th>
<th>Expression</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>hi</td>
<td>7.7</td>
<td>Internal surface heat transfer coefficient [W/m²K]</td>
</tr>
<tr>
<td>he</td>
<td>25</td>
<td>External surface heat transfer coefficient [W/m²K]</td>
</tr>
<tr>
<td>Ti</td>
<td>20</td>
<td>Inside temperature [°C]</td>
</tr>
<tr>
<td>Te</td>
<td>-10 or file</td>
<td>Outside temperature [°C]</td>
</tr>
<tr>
<td>RHi</td>
<td>50</td>
<td>Internal relative humidity [%]</td>
</tr>
<tr>
<td>RHe</td>
<td>100 or file</td>
<td>External relative humidity [%]</td>
</tr>
</tbody>
</table>

(In case of yearly calculations Te and RHe are extracted from an external climate file)

3.1 Calculate the (stationary) 3D thermal bridge effect of the uninsulated steel beams penetrating the insulation material. What is the calculated temperature ratio?

3.2 If we calculate the lowest surface temperature during a year, what is the highest relative humidity (RH) near the coldest surface?

3.3 Make two animations showing the most critical place during the summer and during the winter.

3.4 It was decided that the steel beam should be insulated. Make a proposal for the thickness and kind of insulation. The RH near the coldest surface should not exceed 70 %RH. Show that your design meets this requirement.

3.5 Report your findings using the guidelines of page 3
Exercise 4: Stationary vapour transport

In this part we will make a calculation of the vapor transfer through external walls. We will start with 1D stationary calculations for the three type of walls of Sections 1.1 and 1.2: non insulated wall, internal insulated and external insulated wall.

4.1 Model and simulate the vapor distributions of each of three walls for a typical winter and summer situation (thus in total six variants). Find out what the appropriate material properties and boundary conditions are.

4.2 Plot the vapor pressure across the cross section of each variant

4.3 Make use of the calculated temperatures across the walls from exercise 1. Calculate the saturated vapor pressures from these section temperatures and plot these values in the plot above.

4.4 What are your conclusions from these drawings? Is there a risk for condensation in the cross section of the walls? If so, what are the estimated condensation amounts during a month?

4.5 We can make use of vapor resistant barriers to improve the situation above in case of condensation problems. Repeat the calculations in these cases with a vapor barrier at the indoor and outdoor surfaces and formulate your conclusions.

If you completed this exercise, present your results (informal) to the lecturer in order to get an approval.
Exercise 5: Transient moisture transport

The wetting and drying of concrete and sand-lime brick under isothermal conditions.

The external blade of a vertical construction (width 0.10 m) consists of concrete or sand-lime brick. See following figure.

The concrete and sand-lime brick are both saturated with moisture (rain penetration) caused by a leakage during the past. The problem with leakage has been solved recently. The first goal is to estimate the drying times of both materials.

4.1 Calculate the drying times of both materials, use the material properties at the appendices and steady conditions outside. Furthermore:
- initial moisture content \( w_0 \): (concrete: 150 kg/m\(^3\), sand-lime brick: 250 kg/m\(^3\))
- width: 0.10 m (tip: choose a small height for example 0.005 m, due to symmetry)
- surface coefficient of vapour transfer \( \beta \): 3.10\(^{-6}\) sec/m
- diffusion coefficient \( D_w \): calculate mean values
- boundary conditions: the flow rate \( g \) is zero at all sides, except at the external side where \( g = \beta (P(w) - P_e) \), with \( P_e = 512 \) Pa; \( P(w) = a \cdot w \); (constant \( a \) can be determined using the material properties)

4.2 Calculate again the drying times of both materials, but use functions for diffusion coefficient \( D_w \) and the vapour pressure at the external surface \( P(w) \), determined using the material properties.
The second goal is to investigate whether runoff occurs during heavy rain showers for both materials.

4.3 Calculate the moisture content near the surface during heavy rain showers and evaluate whether runoff occurs for concrete and sand-lime brick. Use the previous model and implement a variable external climate using a file containing the external vapour pressure [Pa] and precipitation [kg/m²s]

Appendices: Material properties for concrete and sand-lime brick

If you completed this exercise, present your results (informal) to the lecturer in order to get an approval.
Baustoff: Beton W/Z = 0.5

Bemerkung:

Rohdichte .................................................. [kg/m³]: 2300
Porosität .................................................. [m³/m³]: 0.18
Wärmeleitfähigkeit ...................................... [W/mK]: 1.6
Feuchtebedingte Zunahme ......................... [%/W-%]: 8
Wasser dampfdiffusionswiderstandszahl trocken ........................................... [-]: 180
Freie (kapillare) Wasserauffüllung .................. [kg/m³]: 180.0
Baustoff: Kalksandstein 1900

Bemerkung:

- Rohdichte: 1900 kg/m³
- Porensättigung: 0.29 m³/m³
- Wärmeleitfähigkeit trocken: 1.0 W/mK
- Feuchtebedingte Zunahme: 8 %/M-%
- Wasserdampfdiffusionswiderstandszahl trocken: 28
- Freie (kapilläre) Wassersättigung: 250.0 kg/m³
Exercise 6: Case 2 Recent Hygro thermal case

At our website we have published the newest case study. See ‘Exercises_2008_Case2.pdf’

Additional Material properties for the moisture capacity ksi [kg/m³]:

<table>
<thead>
<tr>
<th>Material</th>
<th>ksi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>10</td>
</tr>
<tr>
<td>Stone</td>
<td>2</td>
</tr>
<tr>
<td>PUR</td>
<td>1</td>
</tr>
<tr>
<td>Concrete</td>
<td>40</td>
</tr>
<tr>
<td>M. Wool</td>
<td>1</td>
</tr>
<tr>
<td>XPS</td>
<td>1</td>
</tr>
</tbody>
</table>

6.1 Report your findings using the guidelines of page 3