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HAMSTAD Benchmarks using Comsol revisited

Jos van Schijndel*, Sander Goesten & Henk Schellen
Eindhoven University of Technology
* Corresponding author: P.O. Box 513; 5600 MB Eindhoven; Netherlands, A.W.M.v.Schijndel@tue.nl

Abstract: Benchmarks are important tools to verify computational models. In the research area of building physics, the so-called HAMSTAD (Heat, Air and Moisture STAnDardization) project is a very well known benchmark for the testing of simulation tools. In this paper we revisit this benchmark by modeling all five subtasks using Comsol 5.2. Again we conclude that Comsol provides satisfactory results on all benchmarks.

Keywords: Heat, air, moisture, benchmark construction

1. Introduction

Multiphysics tools for modeling heat and moisture transport in constructions, might encounter numerical problems. Especially the multi-layered mixed moisture transport (i.e. vapour and water) part can be tricky to solve.

In 2000, the European Union initiated the HAMSTAD (Heat, Air and Moisture STAndards Development) project on standardization procedures and certification in the field of heat, air, and moisture transport in building constructions (Hagentoft et al 2002, 2004). In the total of five different benchmarks were developed. Amongst others van Schijndel (2007, 2008) developed several models using Comsol to simulate HAMSTAD benchmarks. Although the results were already satisfactory at that time, it did not contain all benchmarks so far. With this paper, we revisit the HAMSTAD benchmarks using the latest version of Comsol (5.2) and present a complete updated overview of all five benchmarks. The models and report (Goesten 2016) are available at the HAMLab (2016) webpage.

2. Model

The heat and moisture transport can be described by the following PDEs using LPc as potential for moisture transfer.

$$C_T \frac{\partial T}{\partial t} = \nabla \cdot (K_{11} \nabla T + K_{12} \nabla LPc)$$
$$C_{LPc} \frac{\partial LPc}{\partial t} = \nabla \cdot (K_{21} \nabla T + K_{22} \nabla LPc) \qquad (1)$$

With:

$$LPc = {}^{10}\log(Pc)$$
$$C_T = \rho \cdot c$$
$$K_{11} = \lambda$$
$$K_{12} = -l_{lv} \cdot \delta_p \cdot \phi \cdot \frac{\partial Pc}{\partial LPc} \cdot Psat \cdot \frac{M_w}{\rho_a RT}, \qquad (2)$$
$$C_{LPc} = \frac{\partial w}{\partial Pc} \cdot \frac{\partial Pc}{\partial LPc}$$
$$K_{22} = -K \cdot \frac{\partial Pc}{\partial LPc} - \delta_p \cdot \phi \cdot \frac{\partial Pc}{\partial LPc} \cdot Psat \cdot \frac{M_w}{\rho_a RT},$$
$$K_{21} = \delta_p \cdot \phi \cdot \frac{\partial Psat}{\partial T},$$

Where t is time [s]; T is temperature [^oC]; P_c is capillary pressure [Pa]; ρ is material density [kg/m^3]; c is specific heat capacity [J/kgK]; λ is thermal conductivity [W/mK]; l_{lv} is specific latent heat of evaporation [J/kg]; δ_p vapour permeability [s]; φ is relative humidity [-]; Psat is saturation pressure [Pa]; M_w = 0.018 [kg/mol]; R = 8.314 [J/molK]; ρ_a is air density [kg/m^3]; w is moisture content [kg/m^3];K is liquid water permeability [s].

3. Implementation of advanced material and boundary functions.

The second extension is the implementation of advanced material and boundary functions using MatLab. These functions are used to convert measurable material properties such as K, φ, δ_p and λ which are dependent on the moisture content into PDE coefficients which are dependent on the LPc and T. This is schematically shown in Figure 1.

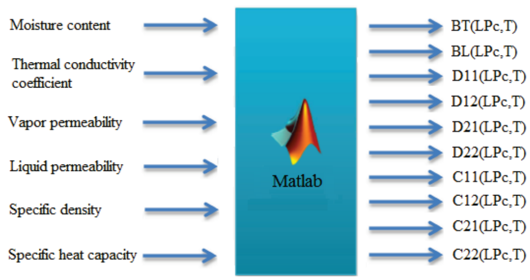

Figure 1. The conversion from measurable material properties into PDE coefficients.

The results for two materials (based on HAMstad benchmark 1) are presented in Figure 2.

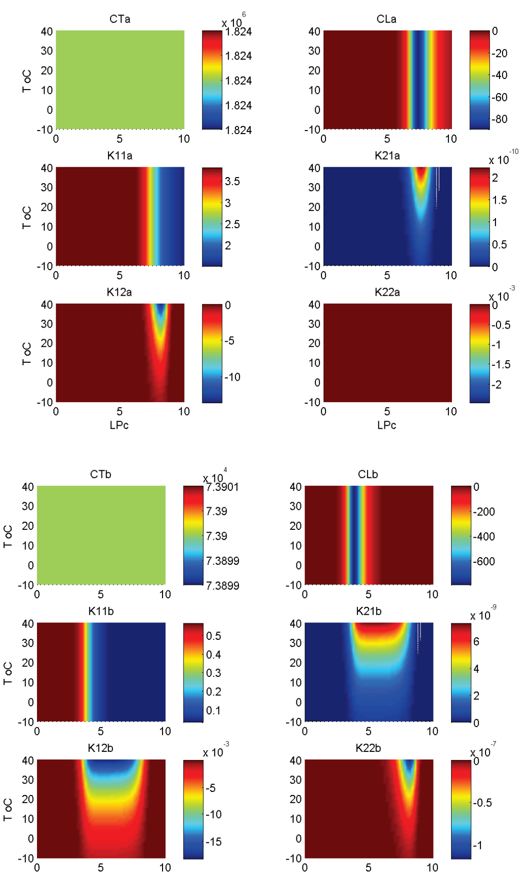

Figure 2. PDE coefficients C_T, C_{LPc}, K_{ij} as functions of LPc and T calculated from the provided HAMSTAD benchmark no.1 material properties for the load bearing (a) and insulation (b) material

For each material and at each point the vapour pressure can be calculated using similar corresponding functions.

4. The benchmarks

In this section we summarise all benchmarks. Due to space limitation only the most important results are shown. Our Comsol results are labelled with HAM-BC 2015, referring to accompanying manual HAM-BC (2015).

4.1 No.1 Heat and moisture with condensation

A roof structure is analyzed in 1D regarding dynamic heat and moisture transport. The thermal insulation is facing the interior and there is a moisture barrier facing the exterior. The structure is perfectly airtight. Figure 3 shows the structure:

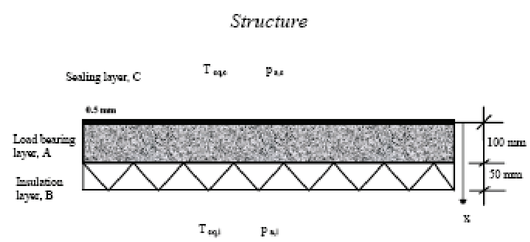

Figure 3. A schematic of the structure of benchmark 1

The properties of the layers are provided in the benchmark including initial conditions.

The boundary conditions are at the (i)nternal (connected with material A):

$$q = h_i \cdot (T_i - T) + l_{lv} \cdot \beta \cdot (p_i - p)$$
$$g = \beta \cdot (p_i - p) \qquad (3)$$

And at the (e)xternal (connected with material B)

$$q = h_e \cdot (T_e - T)$$
$$g = 0 \qquad (4)$$

Where q is heat flux [W/m^2]; h is convective heat transfer coefficient [W/m^{2}K]; β is vapour transfer coefficient [kg/Pam^{2}s]; p is vapour pressure [Pa]; g is moisture flux [kg/m^{2}s]. The boundary conditions T_e, T_i, p_i and p_e are hourly based values provided by benchmark. The most critical part is to simulate the amount of condensation in the insulation layer. Figure 4 shows the bandwidth of the benchmark result.

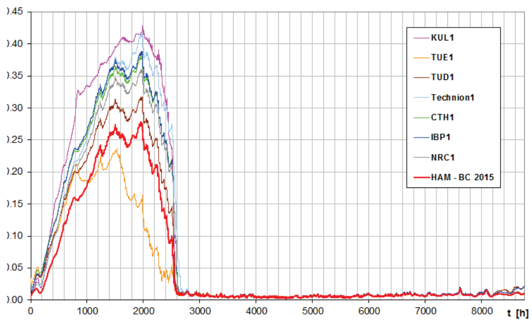

Figure 4. The average moisture content in the insulation.

The result of the COMSOL simulation is quite satisfactory.

4.2 No. 2 Moisture (analytical solution)

The second HAMSTAD-benchmark is about an isotherm drying process of an initially wet 200 mm thick material. The initial conditions are 293 K and a relative humidity of 85%. The indoor boundary conditions are a temperature of 293 K and a relative humidity of 65%. The external side has the boundary conditions consisting of a temperature of 293 K and a relative humidity of 45%. For this benchmark an analytical solution is given. The model in COMSOL consists of a 1D-geometry, see Figure 5.

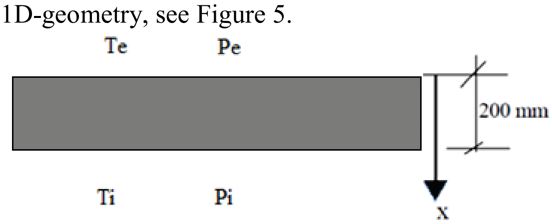

Figure 5. The geometry of benchmark 2

The results of our model are shown in Figure 6, which depicts the moisture content [kg/m^3] across the thickness at 100 hours, 300 hours and 1000 hours. The simulation generates the same results as the analytical solution.

4.3 No. 3 Heat, Air and Moisture

Convective heat and moisture transport is simulated with HAMSTAD-benchmark 3 by inter-computer-model-comparison. A single-plane lightweight construction with a thickness of 200 mm is simulated.

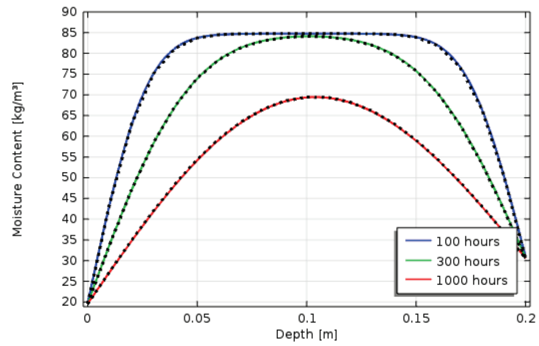

Figure 6. Moisture content [kg/m^3] related to the depth [m] measured from the outside after 100 hours, 300 hours and 1000 hours, where the colored graphs are the results of our model and the dotted graphs are the analytical solutions.

The boundary conditions are constant, with the exception of the pressure difference between indoor and outdoor. First there is infiltration of air, caused by a pressure difference of 30 Pa, which at day 20 will be changed linearly to -30 Pa, which value is reached at day 21, *i.e.* to an exfiltration by an air pressure difference of 30 Pa, see Figure 7.

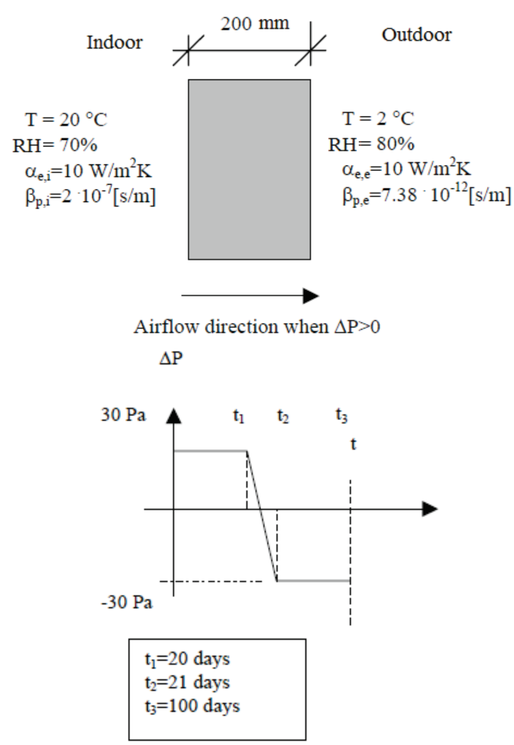

Figure 7. Geometry of the construction of benchmark 3 and the air pressure difference.

For this benchmark we used smaller steps of temperature and logarithmic capillary pressure for the tables of the coefficients generated with MatLab. In Benchmark 1 we used steps of 0.2 Pa for LPc and 1°C for temperature, while here we used 0.01 Pa and 0.05°C. The data for creating the graphs have a time step of 24 hours. The results given in this paper are made with the convection method of Goesten (2016). Figure 8 shows the temperatures near the inner surface. The results of our model are in red.

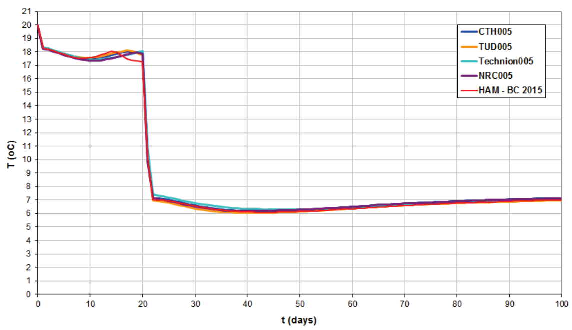

Figure 8. Temperature [°C] related to time [days] at 0.05 m.

Figure 9 presents the moisture content near the inner surface. The moisture content increases at the start with the exfiltration (ΔP = +30 Pa), because the indoor air with the higher absolute humidity in the value of vapor pressure reaches the colder area near the outdoor environment. Both the temperature and moisture content decreases rapidly when the exfiltration (ΔP = +30 Pa) alters to infiltration (ΔP = -30 Pa), which is caused by the fact that the cold and dry air from the outside transports through the construction.

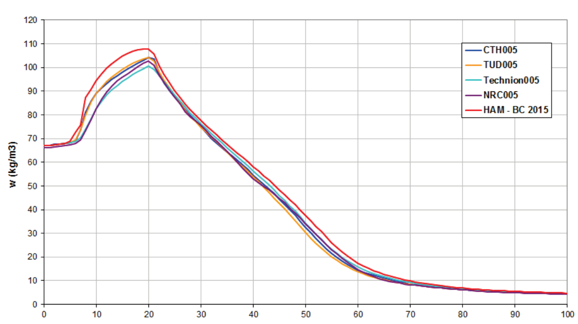

Figure 9. Moisture content [kg/m^3] related to time [days] at 0.05 m.

It is visible in Figure 9 that our Comsol model simulates slightly larger moisture content values between day 8 and day 21 than the other models.

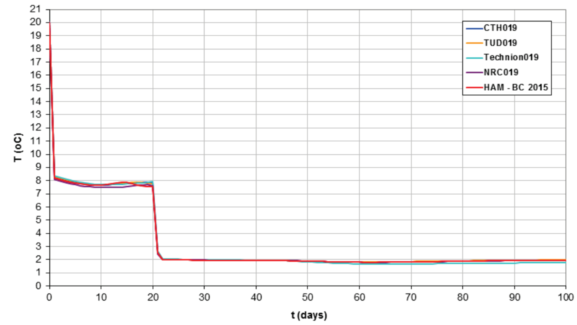

Figure 10. Temperature [°C] related to time [days] at 0.19 m.

Figure 10 and 11 show similar results but now near the outer surface. In Figure 10, the temperature decreases rapidly after the start of the simulation, which is caused by the fact that at the start of the simulation there is a sudden implementation of an air pressure difference of 30 Pa, while there is no initial air pressure difference. So the air pressure difference changes from 0 Pa to 30 Pa in an instant.

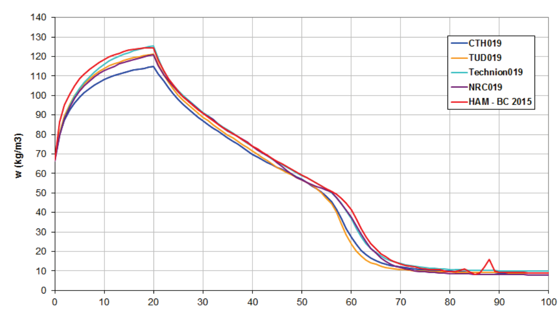

Figure 11. Moisture content [kg/m^3] related to time [days] at 0.19 m.

From Figure 11, at the depth of 0.19 m, there is a little peak at the moisture content between 85 and 90 days, which is caused by the fact that the simulation uses a time step of 24 hours. This deviation does not occur when the time step is set on 1 hour. The description of benchmark 3 instructed the use of a 24 hour time step.

4.4 No. 4 Heat and moisture with rain and sun

The geometry of benchmark 4 consists of a wall with a plaster at the inside, which is submitted to rain and a high temperature caused by solar irradiation (see Figure 12). The structure is airtight; and therefore, no convective heat and moisture transport occurs.. The calculation time is 120 days..

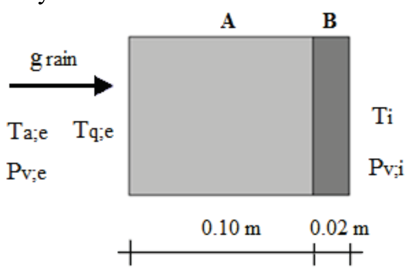

Figure 12. Geometry and boundary conditions of HAMSTAD-benchmark 4.

The temperature at the external surface of the construction is shown in Figure 13. This shows our model generates similar results as the other models for external surface temperature including the influence of rain and solar irradiation. The sudden increase of the temperature is caused by the solar irradiation. The results of Comsol are in blue.

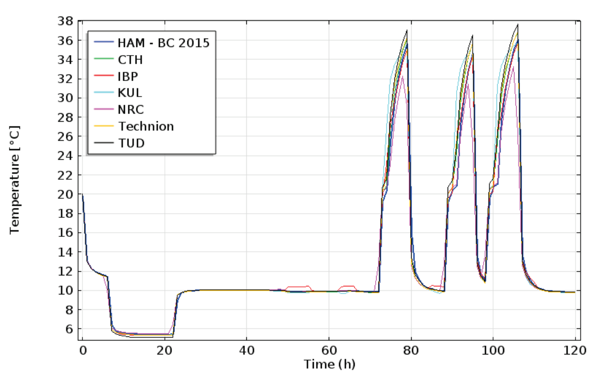

Figure 13. Temperature [^{o}C] related to time [hours] at the external surface.

The moisture content at the external surface is shown in Figure 14, which shows that the influence of the rain flux on the moisture content at the external surface generated by our model leads to similar results as the other simulation models.

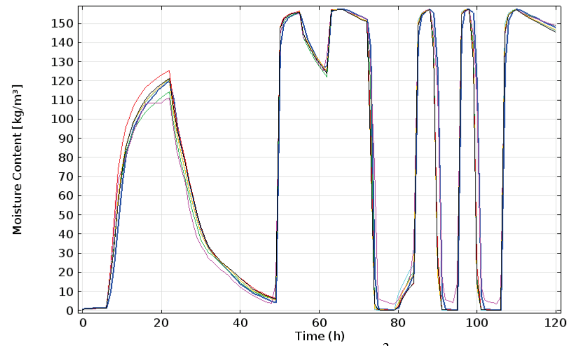

Figure 14. Moisture content [kg/m^3] related to time [hours] at the external surface.

Figure 15 depicts the moisture content over the depth of the construction at 24 hours, which shows that HAM-BC 2015 lead to similar results as the results of the different models from HAMSTAD.

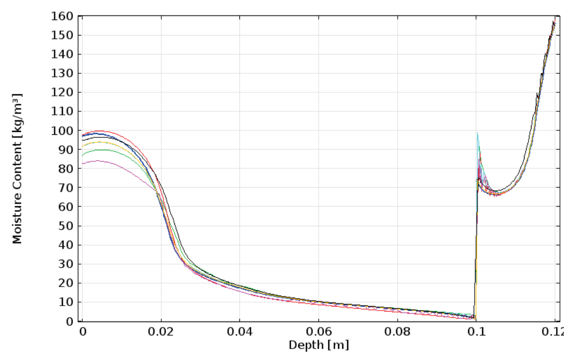

Figure 15. Moisture content [kg/m^3] related to depth [m] on 24 hours.

More results from HAMSTAD-benchmark 4 are shown in Goesten (2016).

4.5 No. 5 Moisture and layer interface

Benchmark 5 is about a wall with insulation applied at the internal side of the construction. The challenges in this benchmark are related to highly non linear material properties and the discontinuities at the interfaces between materials. Figure 16 shows the geometry. It consists at the outside of brick with a width of 365 mm, 15 mm mortar and 40 mm insulation material. The boundary conditions are constant and the results are from the last time step, *i.e.* 60 days. The results are the relative humidity and the moisture content of the last time step at 60 days.

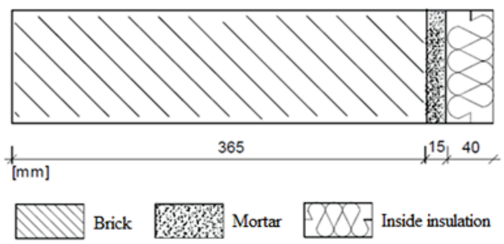

Figure 16. Geometry of the benchmark 5.

The results of HAM-BC 2015 are compared with the average values of benchmark 5 and presented in Figure 17 (relative humidity) and 18 (moisture content).

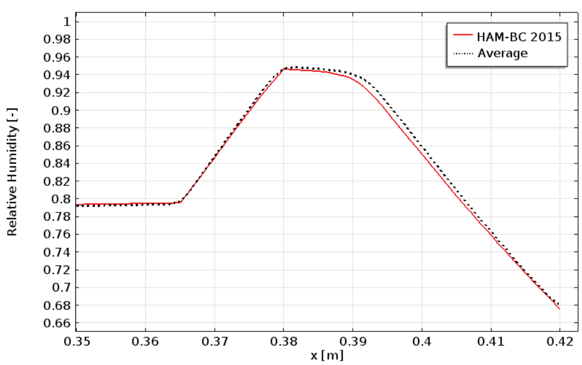

Figure 17. Relative humidity [-] related to the depth [m] on day 60. The result from HAM-BC 2015 is in red. The average results of HAMSTAD are depicted with the dotted line.

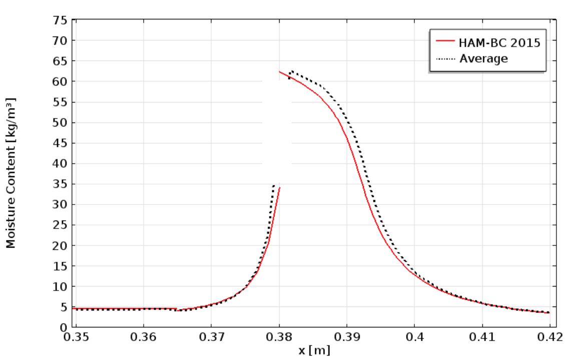

Figure 18. Moisture content [kg/m^3] related to the depth [m] on day 60. The result from HAM-BC 2015 is in red. The average results of HAMSTAD are depicted with the dotted line.

In Figure 18 a discontinuity is visible due to the fact that each material has its own moisture retention curve.

5. Conclusions

In this paper we revisit the HAMSTAD benchmarks by modeling all five subtasks using Comsol 5.2. Again we conclude that Comsol provides satisfactory results on all benchmarks.

The paper is based on the work of Goesten (2016). The thesis and Comsol models are freely downloadable from the HAMLab (2016) website.

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