Benchmarks for One-dimensional Cases of Combined Heat, Air and Moisture Transfer in Building Components

Carl-Eric Hagentoft, Professor
Angela Sasic Kalagasidis, MSc
Bijan Adl-Zarrabi, PhD[1]

Abstract, CIB2004

At present, the certified Glaser method for calculation, prediction and evaluation of moisture performance is considered as rarely applicable. The present state of knowledge, analytical as well as experimental, concerning heat, air and moisture demands updating of standards and certifications. This paper presents five numerical benchmark cases for the quality assessment of simulation models for one-dimensional heat, air and moisture (HAM) transfer. In one case, the analytical solution is known and excellent agreement between several solutions from different universities and institutes is obtained. In the remaining four cases, consensus solutions have been found, with the good agreement between different HAM models. The work presented here is an outcome of the EU-initiated project for standardization of heat, air and moisture calculation methods (HAMSTAD WP2).

1. INTRODUCTION

Starting in the late thirties as a separate research topic, getting a first calculation method for the design of moisture-safe walls based on steady-state diffusion in the fifties (Glaser, 1958), setting the basis for advanced modelling already in the sixties (Philip and Vries, 1957, Luikow, 1966), the combined <u>h</u>eat, <u>a</u>ir and <u>m</u>oisture (HAM) transfer modelling in building physics counts the constant development.

Although the simple, one-dimensional steady-state calculation model proposed by Glaser has been implemented in standards and codes of practise in many countries, it is well known that it can't handle more complicated but normally present cases with in-built moisture, precipitation and air exfiltration. As a result, the construction qualified as being of the good moisture design, in reality, faces the problems of increased moisture content, deterioration, mould growth and etc. due to the effects stated before.

To answer the questions on structure malfunctioning due to the HAM effects, the 'advanced' models, which accounted for the capillary water transport, initial moisture state, latent heat of evaporation and transient conditions, have been more used for prediction of moisture conditions in building enclosures (Van der Kooi, 1971, Sandberg, 1973, Nielsen, 1974, Kiessl, 1983, Kohonen, 1984). Naturally, progress in modelling was followed by advances in computerized calculations (Pedersen, 1990, Künzel 1994, Grunewald 1997), on one side, and measuring techniques of moisture transport properties (see for example Roels et. al, 2003), on the other.

The first international gathering of researchers in this area was around the project '<u>H</u>eat-<u>A</u>ir-<u>M</u>oisture <u>T</u>ransport in highly <u>I</u>nsulated new and retrofitted <u>E</u>nvelope Parts' (HAMTIE), Annex 24, initiated in 1990 by International Energy Agency. The project results were published in reports on model development and comparison (Hens, 1996), material properties (Kumaran, 1996), boundary conditions (Sanders, 1996) and performances (Hagentoft, 1996); up to now, they give an excellent overview of the summarized

[1]C-E Hagentoft is professor and A. Sasic Kalagasidis is PhD student at the Department of Building Technology, Building Physics Division, Chalmers University of Technology, Sweden; B. Adl-Zarrabi is senior researcher at the Swedish National Research and Testing Institute, Borås, Sweden.

knowledge in this area together with the streamlines and tendencies for future development and advances.

The HAMSTAD project (acronym stands for Heat, Air and Moisture Standards Development), which focused on the standardization procedures and certification in this field, appeared as a natural connective in this chain of development and international collaboration. The project was initiated by the European Commission at the end of the year 2000, with the main objective to implement the present knowledge of HAM-modelling in standards and other reference documents relevant for practice. Instead of a system of deterministic and prescriptive pre-standards on modelling requirements for the development and commercialization of numerical codes, an 'open methodology' is proposed. One of the project outcomes are five benchmark cases that cover a whole range of HAM-related building design problems.

2. BENCHMARK HAM MODELLING

The numerical solution of the five benchmark cases are based on the mathematical model for one-dimensional heat, air and moisture transfer in porous building enclosures, which is fully described in the main modelling document (Hagentoft, 2002a). The proposed model covers heat and mass balance, heat, air and moisture transfer, exterior and interior boundary and climate conditions, and is presented hereafter in brief.

Moisture transfer equations

The moisture transfer is divided into one in vapour phase and one in liquid phase.

$$g = g_v + g_l \qquad (1)$$

For the liquid flow we have:

$$g_l = K \cdot \frac{\partial P_{suc}}{\partial x} \qquad (2)$$

where

K = hydraulic conductivity, which depends on the moisture and temperature conditions.

The vapour phase flow is then divided into one due to diffusion (the first part) and one due to convection (the second part).

$$g_v = -\delta_p \cdot \frac{\partial p}{\partial x} + r_a \cdot v_a \qquad (3)$$

where

δ_p = vapour permeability, which is moisture dependent

v_a = water vapour content or the humidity by volume.

The airflow through the structure, r_a, is driven by air pressure differences across the structure. The model assumes a constant volume airflow rate through the whole structure, allowing for variations in time. In the modelling document (Hagentoft, 2002a) the moisture transfer is expressed using various alternative potentials than reported above.

Heat transfer eqations

The heat flow has one conductive and one convective part:

$$q = q_{cond} + q_{conv} \tag{4}$$

The conductive part reads:

$$q_{cond} = -\lambda \frac{\partial T}{\partial x} \tag{5}$$

where

λ = thermal conductivity, normally dependent on the moisture conditions of the material.

The convective part inside the materials becomes:

$$q_{conv} = r_a \rho_a c_{p,a} T + g_v l_{lv} \tag{6}$$

where

$c_{p,a}$ = specific heat capacity of air at constant pressure, in J/kg K.

l_{lv} = specific enthalpy of liquid-vapour phase change, in J/kg.

The second term accounts for the transfer of latent heat.

The model has some limitations such as:

- Temperature should be in the range of 0 °C to +80 °C.
- Effects associated with phase change, liquid to ice, are neglected.
- Climatic load due to driving rain is simplified.
- No hysteresis is accounted for.
- No chemical reactions are considered.
- Ageing effects or changes in the geometrical dimensions are neglected.

3. OUTLINE OF THE BENCHMARK CASES AND SOME RESULTS

Benchmarks presented in this section cover heat, air and moisture transfer. Each benchmark covers at least two transfer mechanisms. The cases have been selected in order to cover various combinations of climatic loads and material combinations. All benchmarks are presented in brief, illustrating some important features. A more detailed reporting of the benchmarks and the modelling results can be found in (Hagentoft 2002b), and also on www.buildphys.chalmers.se, available for download.

Up to seven different transient temperature and moisture solutions for the selected five benchmarks have been obtained. Due to the inherent non-linearity and coupling of the phenomena, analytical solutions exist only for simple decoupled cases. For such a case within this work, deviations between numerical and analytical solution were exactly evaluated. For the remaining four cases, the true solutions are not known but the approximate ones of different laboratories. And for such cases, the consensus solution was found either after detailed comparison of temperature and moisture profiles at certain time-steps and at certain positions, insuring the same trend and response, or within the ‘band of acceptance’ which is statistically defined (see more in Benchmark 1). It is worth to mention that there is no certainty that the average of numerical solution is the good solution. However, it has been assumed that the correct solution lies close to the ones, which show a close agreement.

Benchmark 1: Insulated roof

The first benchmark considers an internally insulated roof with (known) problems of interstitial condensation that occurs at the contact surface between the load bearing and insulating material. The structure is perfectly air tight, and no vapour exchange is possible with an exterior. Applied external climatic load corresponds to the North-European conditions, while the internal climate is the one normally detected in dwellings. The simulation covers five years. Some results on the moisture content variations in time are presented in following figures.

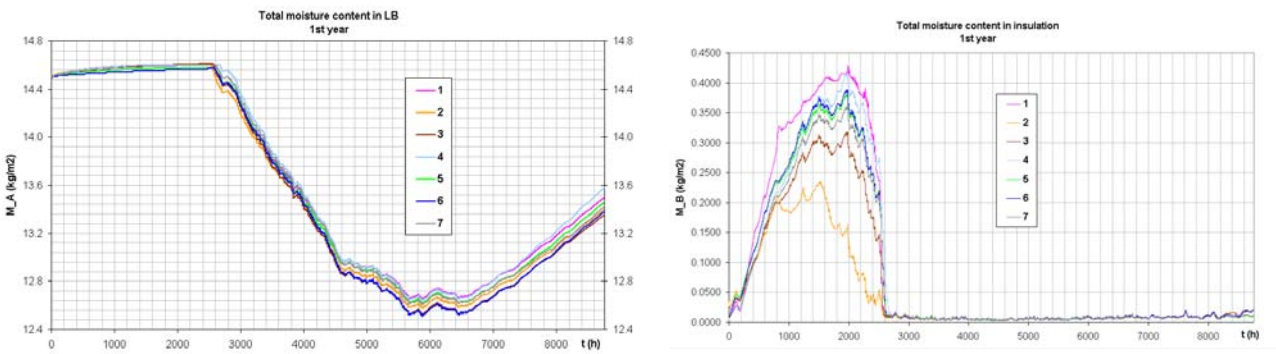


Figure 1. Total moisture content in the load bearing and insulation layer during the first year.

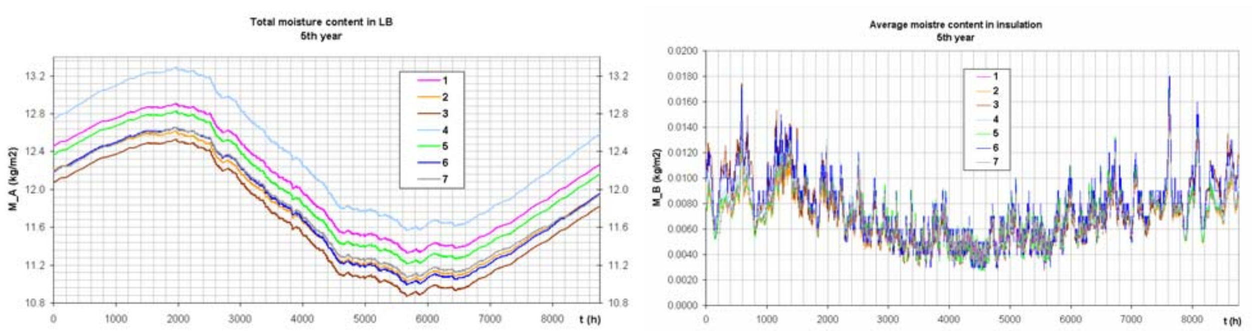


Figure 2. Total moisture content in the load bearing and insulation layer during the fifth year.

The results show reasonably good similarity. The greatest deviations occur in the moisture content results of the insulation layer during the first year. Results for the moisture contents in the load bearing layer are getting more and more disperse year after year, even though they are reasonably well grouped. For this case, the consensus solution was found within the 'band of acceptance', which is illustrated in Figure 3 and 4.

Upper and lower thresholds of the 'band' are defined on the basis of analogy with t-distribution (Råde et al. 1988), a statistical method for treating random data where the number of observations is low. Under such conditions the t-distribution gives a better confidence interval than the normal distribution. Sometimes, during specific time sequences, this procedure must be altered. For instance when relative humidity is considered, for physical relevance the minimum and maximum must be between 0 and 100%. The general procedure for definition of this band of acceptance is presented in the project report (Hagentoft, 2002b).

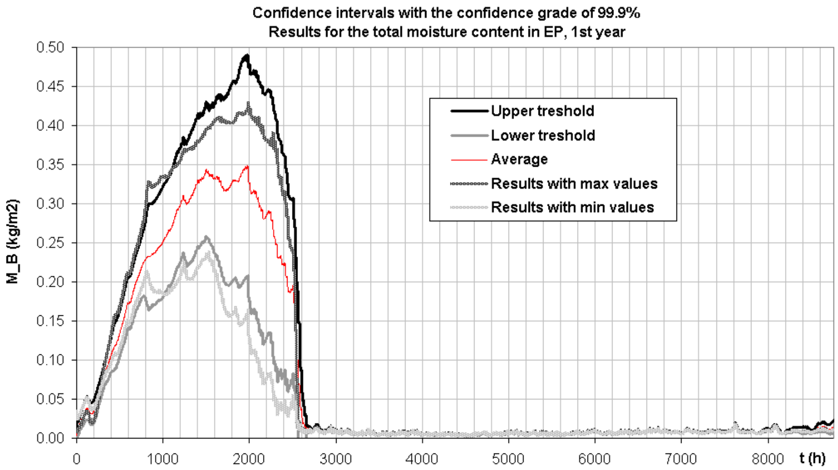


Figure 3. The band of acceptance for the total moisture content in the insulating layer during the first year, with a confidence interval of 99.9%.

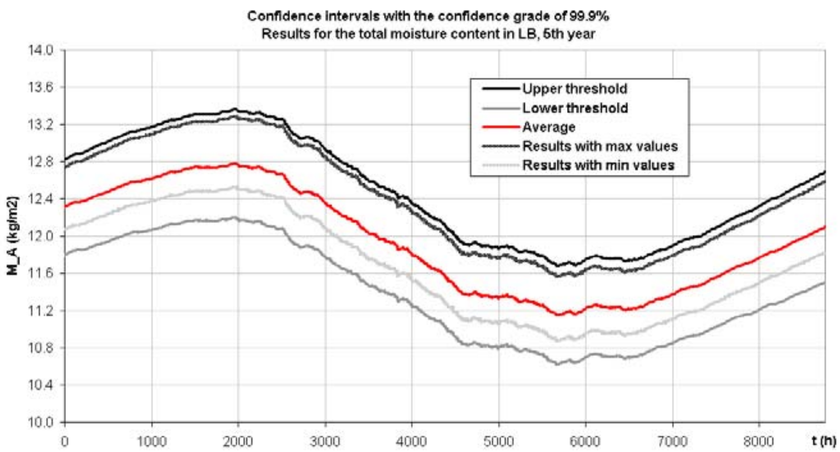
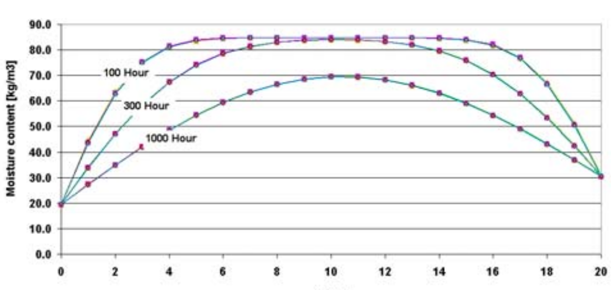


Figure 4. The band of acceptance for the total moisture content in the load bearing layer during the fifth year, with a confidence interval of 99.9%.

Benchmark 2: Analytical case

The second benchmark deals with the moisture redistribution in a single homogeneous material layer under isothermal conditions. The layer is initially in moisture balance with the ambient air, having a constant relative humidity. The drying of the material is caused by sudden changes in relative humidity of the surroundings, different at the two sides. The structure is perfectly airtight and simulations cover 1000 hours. This case has an analytical solution.



Distribution of moisture content for six different numerical solutions, after 100, 300 and 1000 hours across the wall are shown in Figure 5. All numerical solutions show an excellent agreement with the analytical solution.

Figure 5. Results for the moisture content distribution across the wall after 100, 300 and 1000 hours.

Benchmark 3: Lightweight wall

The third benchmark deals with an air transfer through one material layer. Moisture transfer is caused mainly by the airflow through the layer, but also by the moisture and temperature gradients across the layer. The external side is vapour tight but air-open. The simulation time is 100 days. During the first 20 days there is an air exfiltration, which is then replaced by an air infiltration period. The temperature and moisture distribution in time in the middle of the layer are shown in Figure 6. The four numerical solutions show very good agreement for all positions and times.

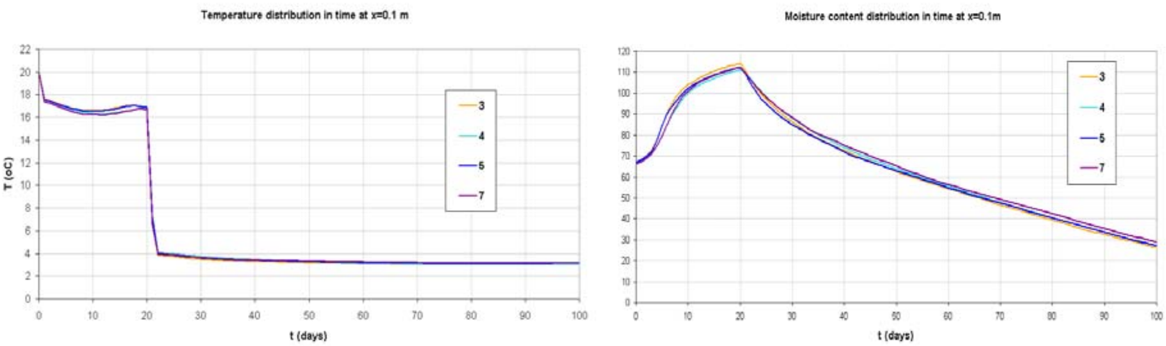


Figure 6. Temperature and moisture variations in time in the middle of the layer (x=100 mm).

Benchmark 4: Response analyses

The fourth benchmark deals with the moisture movement inside the wall with hygroscopic finishing material. The exterior part is 100 mm thick and the thickness of the finishing material is 20 mm. The wall is submitted to subsequent changes in relative humidity, heat and moisture loads at the inner and outer surface, as it is presented in Figure 7. The structure is perfectly airtight. The simulation time is 4 days.

The climatic load is rather severe, generating different heat and moisture phenomena like moisture condensation induced by cooling, alternative drying and wetting, moisture redistribution across the contact surface between two capillary active materials, etc. The case is more complicated with selected materials, having an extremely fast liquid transfer in the first material.

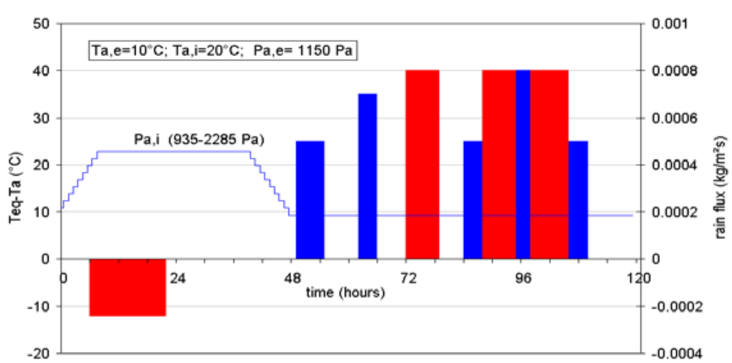


Figure 7. External and internal climatic loads. Heat load from exterior is given in terms of differences between external equivalent, $T_{eq,e}$, and internal, $T_{a,i}$, air temperature. Moisture load at external surface is given as the rain flux, and on internal side as the variations in water vapour partial pressure, $p_{a,i}$, at constant temperature.

The consensus solution for this benchmark is obtained after detailed evaluation of temperature and moisture profiles coming from six different numerical solutions. For example, Figure 8 - 9 show results for moisture content and temperature at external and internal surfaces, during the whole simulation time. The agreement among different solutions is very good. Somewhat bigger differences occur when solar radiation takes place. Figure 10 shows results for the moisture content and temperature across the wall, after the first wetting. The agreement is still very good, but the one can observe the differences in treating the wetting processes. At the end of the simulation time, Figure 11, all results show the same moisture and temperature distribution over the wall.

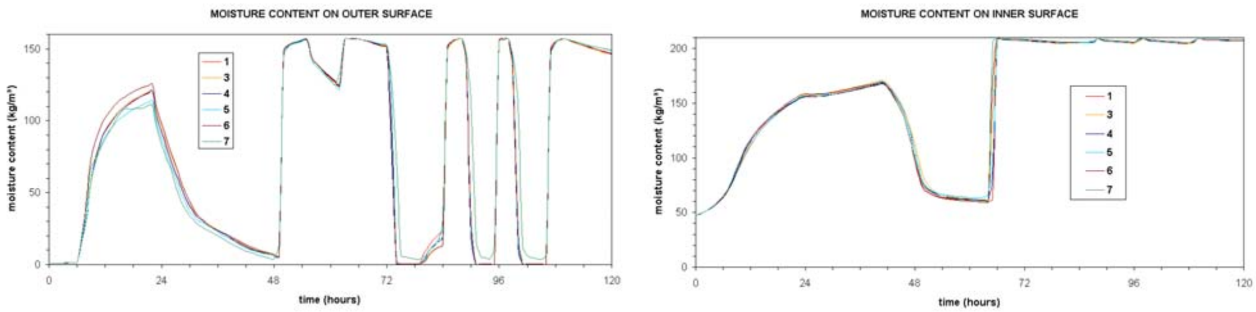


Figure 8. Moisture content at the outer and inner surface during the simulation period.

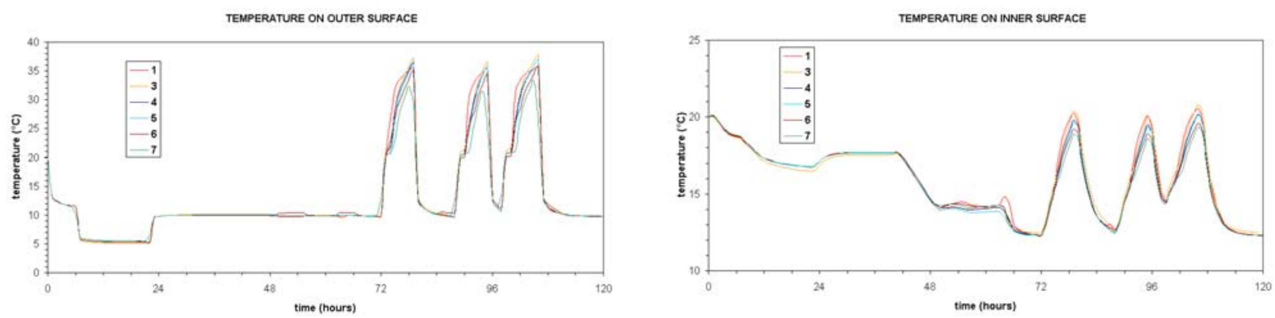


Figure 9. Temperature variations at the outer and inner surface during the simulation period.

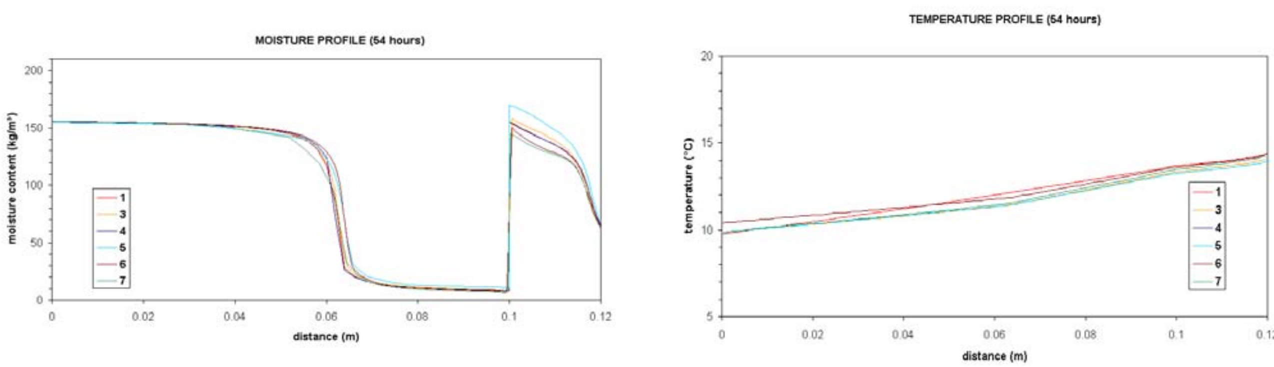


Figure 10. Moisture content and temperature distributions through the structure after 54 hours.

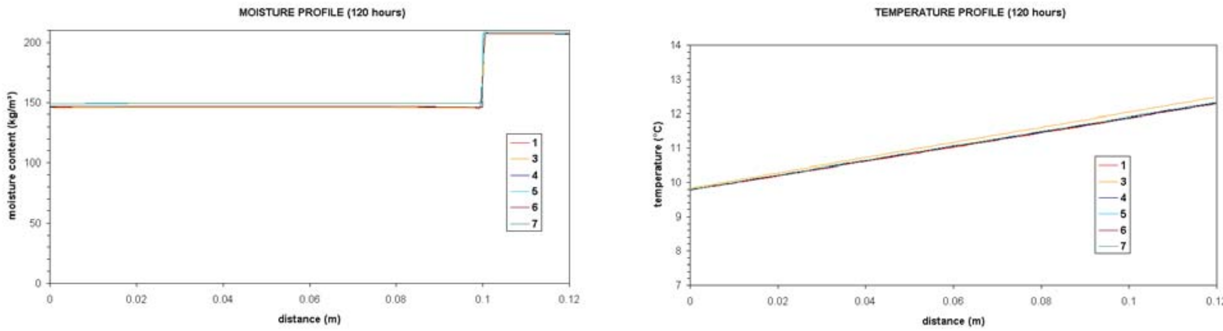


Figure 11. Moisture content and temperature distributions through the structure after 120 hours

Benchmark 5: Capillary active inside insulation

The fifth benchmark deals with the moisture redistribution inside a wall with capillary active inside insulation. The wall consists of three layers: brick (365 mm), mortar (15 mm) and insulating material (40 mm). The structure is airtight. Thermal conductivities of the brick and the insulating material differ by factor 11 (at dry conditions). The initial temperature and moisture content are constant. At time zero there is a sudden change in temperature and vapour pressure at both the interior and exterior side. The simulation time is 60 days. Six different numerical solutions show rather good agreement for all positions, Figure 12.

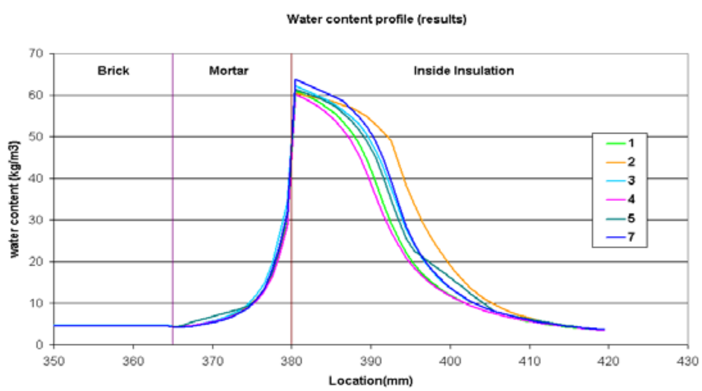


Figure 12. Moisture distribution (water content) at the interior side of the structure after 60 days.

4. DISCUSSION AND CONCLUSIONS

Numerical solutions are produced using different software packages, based on the same mathematical model but with varying numerical techniques. Some of them are based on finite differences (FDM), the other on finite volumes (FVM) or finite elements (FEM), with explicit or implicit time discretization schemes. They differ in discretization strategies (constant or adaptive time steps and mesh), in treating non-linear phenomena (i.e. interpretation of interface conductivity), in applied convergence criteria (absolute, relative), interpolation and iterative methods. Although boundary conditions were hourly based, they were also implemented in different ways: whether as a step function, keeping the constant value between two consequent time steps, or some linear interpolation was performed within the time step. It was also shown that the implementation of material data had significant importance. In the most cases they are given and implemented as functions, but some softwares were able to use them only like tables of values, with different refinement.

By this, the most of all kind of numerical techniques were covered and proved for being able to produce sufficiently good results. Although the exact solution was known only for one of the cases, the definition of the ‘sufficiently good results’, or more appropriate consensus solutions had to be found using some statistical methods, what is more described further below. It was shown that stated differences are the main cause for not producing the same results, or in some cases with better agreement, even though the mathematical model was the same.

From the various numerical results presented for the benchmark cases it is shown that reasonable consensus solutions can be found. It must be kept in mind that the simulations account for very complicated non-linear processes. Even though, in principle, it is a matter of pure mathematics to solve the same sets of equations, it is still very complicated. Differences in algorithms for solving the equations, mesh densities, different numerical accuracy together with varying sets of used potentials (including complicated transformations) are the causes to different results. Nevertheless, for the first time an elaborate work on quality assessment of HAM-models are presented. This will give a platform for control of the accuracy of existing HAM-software and encourage development of new ones.

Acknowledgment

This paper is relied on the HAMSTAD WP2 final project results, which are to be reported as a draft paper (Hagentoft et al. 2003). Authors are greatly acknowledged to all participants in the project who helped with their contributions in benchmark results, processing the same and discussion and suggestions in presenting them: Jan Carmeliet, Hugo Hens and Staf Roels, Catholic University of Leuven, Belgium, Reda Djebar and Kumar Kumaran (voluntarily participation), National Research Council of Canada, John Grunewald and Max Funk, Technical Universitiy of Dresden, Germany, Rachel Becker and Dina Shamir, Technion Israel Institute of Technology, Olaf Adan and Harold Brocken, TNO Building and Construction Research, the Netherlands. We would like to thank also those who voluntarily participated in the project with benchmark results: Andreas Holm and Hartwig Künzel, Fraunhofer Institute for Building Physics, Germany and Jos van Schijndel, Eindhoven University of Technology, the Netherlands.

Nomenclature

c_p	Specific heat capacity at constant pressure (J/kgK)
g	Density of moisture flow rate (kg/m^{2}s)
l_{lv}	Latent heat of evaporation (J/kg)
p	Partial vapour pressure (Pa)
P_{suc}	Suction pressure (Pa)
q	Density of heat flow rate (W/ m^2)
r_a	Density of air flow rate (m^3/ m^{2}s)
T	Temperature (˚C)
v	Humidity by volume (kg/m^3)
δ_p	Moisture permeability (s) or (kg/m s Pa)
λ	Thermal conductivity (W/mK)
ρ	Density (kg/ m^3)

References

Glaser H., 1958. Temperatur und Dampfdruckverlauf in einer homogene Wand bei Feuchteausscheidung. Kältetechnik, 6, pp 174-181.

Grünewald J. 1997. Diffusiver und konvektiver Stoff- und Energietransport in kapillarporösen

Baustoffen. Dissertation an der Technischen Universität Dresden.
Hagentoft, C-E. 1996. Final Report, Volume 5, Task 5: Performances and Practice. IEA-Annex 24, ACCO, Leuven.
Hagentoft, C-E. 2002a. HAMSTAD – WP2 Modeling, Version 4. Report R-02:9. Gothenburg, Department of Building Physics, Chalmers University of Technology.
Hagentoft, C-E. 2002b. HAMSTAD – Final report: Methodology of HAM-Modeling. Report R-02:8. Gothenburg, Department of Building Physics, Chalmers University of Technology. Benchmarks can be downloaded from www.buildphys.chalmers.se
Hagentoft, C-E., Adan, O., Adl-Zarrabi, B., Becker, R., Brocken, H., Carmeliet, J., Djebbar, r., Funk, M., Grunewald, J., Hens, H., Kumaran, K., Roels, S., Sasic Kalagasidis, A., Shamir, D. 2003. Assessment Method of Numerical Prediction Models for Combined Heat, Air and Moisture Transfer in Building Components. Benchmarks for One-dimensional Cases. 2002b. To be published in Journal of Thermal Envelope and Building Science, SAGE Publications.
Hens, H. 1996. Final Report, Volume 1, Task 1: Modelling. IEA-Annex 24, ACCO, Leuven.
Kiessl, K., 1983. Kapillarer und dampfförmiger Feuchtetransort in mehrschichtigen Bauteilen: Technerische Erfassung und bauphysikalische Anwendung (Dissertation). Universität-Gesamthochschule - Essen.
Kohonen R. 1984. A Method to Analyse the Transient hygro-thermal Behaviour of Building Materials and Components. Technical Research Center of Finland (VTT), Publication 21.
Kumaran, K. 1996. Final Report, Volume 3, Task 3: Material properties. IEA-Annex 24, ACCO, Leuven.
Künzel H. M. 1994. Verfahren zur ein- und zweidimensionalen Berechnung des gekoppelten Wärme- und Feuchtetransports in Bauteilen mit einfachen Kennwerten. Dissertation an der Universität Stuttgart.
Luikow, A. V. 1966. Heat and Mass Transfer in Capillary-porous Bodies. London: Pergamon Press.
Nielsen, A. F. 1974. Moisture Distribution in Cellular Concrete During Heat and Moisture Transfer. Ph.D. thesis. (In Danish). Thermal Insulation Laboratory, Technical University of Denmark.
Pedersen, C. R. ,1990. Combined Heat and Moisture Transfer in Building Constructions. Ph.D. thesis. Thermal Insulation Laboratory, Technical University of Denmark.
Philip, J. R., and de Vries., D.A. 1957. Moisture Movement in Porous Materials under Temperature Gradients. Transactions, American Geophysical Union 38:222-232.
Roels, S., Carmeliet, J., Hens, H. 2002. HAMSTAD, WP1, Final Report Moisture Transport Properties and Material Characterization, KU Leuven, Belgium.
Råde L., Westergren B., 1998. *BETA,* Mathematics Handbook for Science and Engineering, Studentlitteratur, Lund, Sweden.
Sandberg, P.I. 1973. Moisture Balance in Building Elements exposed to Natural Climatic Conditions. (In Swedish). Division of Building Technology, Lund Institute of Technology. Report 43, Lund, Sweden.
Sanders, C. 1996. Final Report, Volume 2, Task 2. Environmental Conditions. IEA-Annex 24, ACCO, Leuven.
van der Kooi, J. 1971. Moisture Transport in Cellular Concrete Roofs. Ph.D thesis. Delft, the Netherlands: Uitgeverij Waltman.