Comparison of calculated and measured values of wall assembly tests using Delphin 5

Anssi Laukkarinen, M.Sc. student
Juha Vinha, Associate Professor

Tampere University of Technology, Finland

KEYWORDS: *Delphin 5, HAM-modelling, wall assembly tests*

SUMMARY:
HAM-calculation program Delphin 5 was used to simulate previously made laboratory experiments of different timber-framed wall assemblies. Laboratory experiments consisted of wall assembly tests and of material tests including the definition of moisture retention isotherm in the hygroscopic range, water vapor diffusion resistance factor, water absorption coefficient and thermal conductivity.

Liquid transport coefficient was not measured but acquired with calculations and material test simulations. The division of total moisture flow from cup test measurements into vapor and liquid flow was also noticed to have an effect to the results. This text presents the procedure used for describing the material properties for Delphin 5 and the results of three wall assembly simulations with the measured material properties available.

1. Introduction

1.1 Background

To be able to make more comprehensive calculations than in previous projects, Delphin 5 was studied. Hygrothermal behavior of timber-framed wall assemblies was simulated to understand how the program works and to verify its calculation results. Creating own material files was an objective also.

The sorption isotherm and water vapor diffusion resistance factor in the hygroscopic range, water absorption coefficient and thermal conductivity were defined for materials used in wall assembly experiments. As these measurements lack the moisture capacity data in the overhygroscopic range and liquid water conductivity/diffusivity data, material test simulations were made to determine the necessary parameters.

Validation calculations against field measurements with different simulation programs have presented for example Airaksinen (2003), Sasic Kalagasidis (2004), Vinha (2007) and Kalamees & Kurnitski (2010).

1.2 Description of studied wall assemblies

Wall assembly tests have been reported previously by Vinha (2007). The structure, measurement points and a schematic view of the interior and exterior air conditions are presented in Figure (1).

The cladding and ventilation gap were excluded from the calculations. To eliminate the effect of surface transfer coefficients the relative humidity at surface was calculated from the relative humidity of air. This was done by keeping the water vapor pressure constant and changing the water vapor pressure at saturation according the temperature change from air to surface. The values were fed to the program as air conditions and the water vapor exchange coefficient was set thousandfold with respect to the default values (β_i = 3E-8 s/m and β_e = 2E-7 s/m). The measured surface temperature was fed directly to the program.

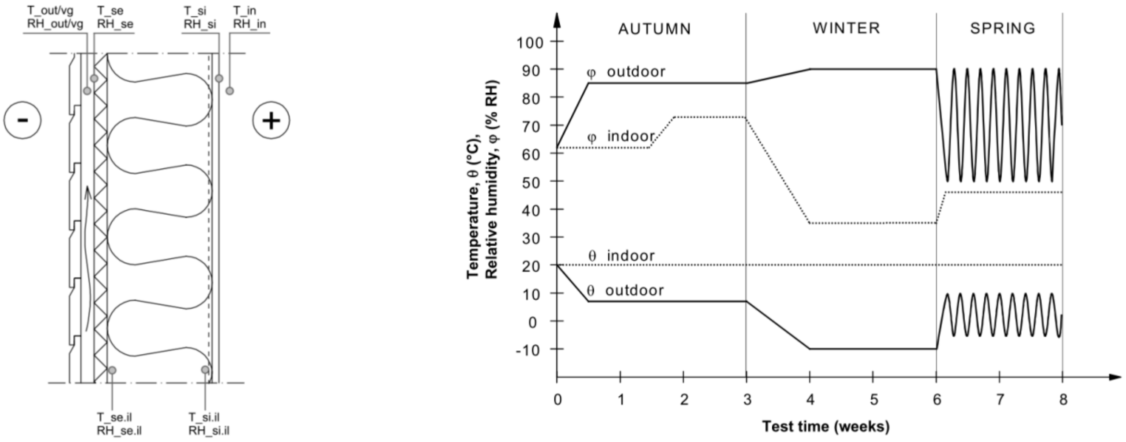

FIG (1). Left: Overview of the structure. Right: Schematic view on the interior and exterior air conditions.

The conditions on the interior and exterior surface of the insulation layer were measured. Because the measurement probe was approximately 13 mm thick the monitoring point was selected to be 6.5 mm to the insulation layer from the adjacent surfaces. Studied wall assemblies are given Table (1).

TABLE (1). Wall assemblies studied in the simulations and their layers from inside out

Name	Interior board	Air/Vapor barrier	Insulation layer	Sheathing
3b	Gypsum board 13 mm	Bitumen paper	Cellulose insulation 173 mm	Wood fibreboard 25 mm
12b	Gypsum board 13 mm	Bitumen paper	Glass wool 198 mm	Wood hardboard 4.8 mm
29b	Gypsum board 13 mm	Plastic foil + spruce plywood 9 mm	Cellulose insulation 173 mm	Spruce plywood 9 mm + glass wool 25 mm

1.3 Calculation results from earlier studies

Wall assembly 3b has been a part of a previous study also (Vinha 2007 and Kalamees 2003). In those studies the conditions inside the structure were calculated with three different hygrothermal calculation programs: 1D-HAM, MATCH and WUFI-2D. The calculation results of relative humidity at the exterior and interior surfaces of the insulation layer are presented in Figure (2).

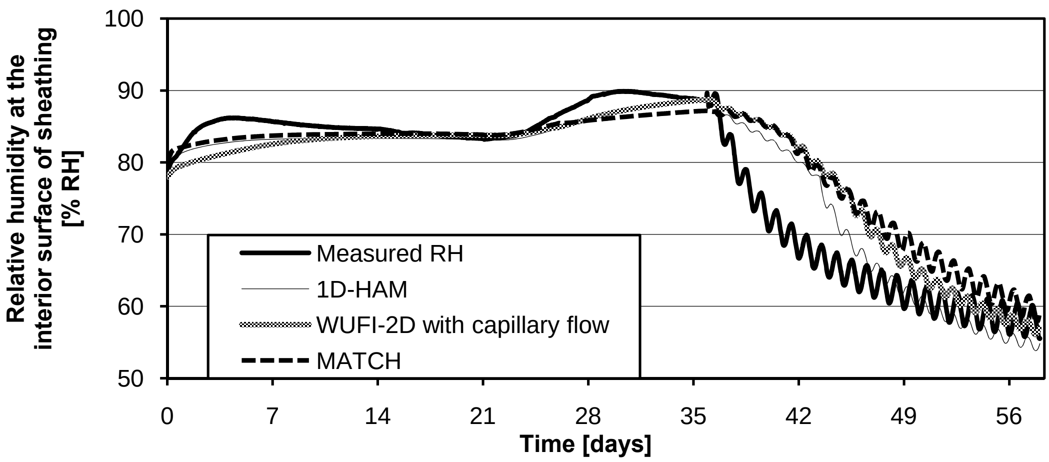

FIG (2): Calculation results from a previous study of the wall 3b.

2. Material functions

One key parameter in HAM-calculations is the moisture retention curve (Grunewald 2003). From the material tests the w(RH) values were available in the hygroscopic range. This is only a part of the whole moisture content range. For the overhygroscopic range the shape of the curve was taken from a suitable library material and fitted to the measured values to form a smooth and continuous curve covering the whole moisture content range.

2.1 The basic equations

The Kelvin equation relates the relative humidity of air to the capillary pressure in the material pores in an equilibrium.

$$\phi = \exp\left(-\frac{p_c}{\rho_l R_v T}\right) \quad (1)$$

Where ϕ is the relative humidity [-]
p_c is the capillary pressure or suction [Pa]
ρ_l is the density of water [kg/m^3]
R_v is the gas constant for water vapor [J/(kg·K)] (461.4 J/(kg·K))
T is the absolute temperature [K]

Moisture content of a material can be represented as the water volume per material volume (θ [m^3/m^3]), water mass per material volume (w [kg/m^3]) or water mass per dry material mass (u [kg/kg]).

The connection between the first two is:

$$\theta_l \rho_w = w \quad (2)$$

Where θ_l is moisture content, water volume by material volume [m^3/m^3]
ρ_w is water density [kg/m^3]
w is moisture content, water mass by material volume [kg/m^3]

Definition of characteristic moisture storage parameters are found in Grunewald (2003). The effective saturation moisture content θ_{eff} is the pore volume which can be filled by water and dissolved air without entrapped air. It is the upper limit of the moisture retention curve for desorption. Capillary saturation moisture content θ_{cap} describes the amount of water that can be absorbed to material by capillary forces from a free water surface. The value is also time-dependent.

Knowing the effective saturation moisture content, it is possible to represent the amount of liquid water in material as a relative proportion according the following equation:

$$\Theta_l = \frac{\theta_l - \theta_{dry}}{\theta_{eff} - \theta_{dry}} \quad (3)$$

Where θ_{dry} is the moisture content of a dry material [m^3/m^3]

The diffusion resistance factor μ [-] was determined for materials by the cup method closely according the method presented in EN ISO 12572 (2001). The water vapor mass flow through a material layer can be calculated using the Fick's law

$$g_v = -\frac{D_v}{\mu}\frac{\partial v}{\partial x} \quad (4)$$

Where g_v is water vapor flow rate through material layer [kg/(m^{2}s)]
D_v is water vapor permeability of stagnant air [m^2/s]
μ is the diffusion resistance factor [-]
$\partial v/\partial x$ is the water vapor gradient [Pa/m]

The liquid water conductivity K_l [s] is a material parameter which relates the liquid water flow to the suction gradient. The liquid water diffusivity D_l [m^2/s] relates the liquid water flow to the moisture content gradient. The liquid water flux can be calculated according to the following equations:

$$g_l = K_l \frac{\partial p_c}{\partial x} \qquad (5)$$

$$g_l = -D_l \frac{\partial w}{\partial x} \qquad (6)$$

Setting the two flows equal the relation between the liquid water conductivity and diffusivity is

$$K_l = D_l \frac{\partial w}{\partial p_c} \qquad (7)$$

The values are calculated using the moisture retention curve. The relation between water vapor diffusivity and liquid water diffusivity can be calculated with the sorption curve by setting equations (4) and (6) equal.

$$D_l = \frac{D_v}{\mu}\frac{\partial v}{\partial w} = \frac{D_v}{\mu}\frac{v_{sat}}{\partial w / \partial \phi} \qquad (8)$$

2.2 Separation of liquid water flow from the total moisture flux in cup tests

Water vapor diffusion is described in Delphin 5 with the diffusion resistance factor of a dry material and a material function which describes how the water vapor permeability changes at different relative moisture contents. The default function of Delphin 5 for water vapor diffusivity was used in the calculations. It drops linearly from the water vapor permeability of dry material to zero as a function of the relative moisture content.

The water vapor flux was calculated apart from the total moisture flux and the remaining part was interpreted as liquid water flow.

$$g_l(\Theta) = g_{tot}(\Theta) - g_v(\Theta) \qquad (9)$$

Where
- g_l is the liquid water flux [$kg/(m^2s)$]
- g_{tot} is the total moisture flux in the cup test [$kg/(m^2s)$]
- g_v is the water vapor flux calculated with the default water vapor permeability function [$kg/(m^2s)$]

The liquid water conductivity in the hygroscopic range can be calculated using the formulae presented.

$$K_l = -\left(\frac{1}{\mu} - \frac{1}{\mu(\Theta)}\right) D_v v_{sat} \left(-\frac{\phi}{\rho_w R_v T}\right) = \left(\frac{1}{\mu} - \frac{1}{\mu(\Theta)}\right) D_v v_{sat} \left(\frac{\phi}{\rho_w R_v T}\right) \qquad (10)$$

The moisture retention curve can be used to define the relative liquid water conductivity function in the overhygroscopic range. The theory can be found in Scheffler & Plagge (2010). The following equation was used to calculate the relative liquid water conductivity function:

$$K_{l,rel}(\theta_l) = \frac{\int_0^{\theta_l} p_c(\theta)^{-2} d\theta}{\int_0^{\theta_{eff}} p_c(\theta)^{-2} d\theta} \qquad (11)$$

A trend curve of polynomial type was fitted to the $K_{l,rel}$-function. It was truncated from the capillary saturation moisture content if necessary. The liquid water conductivity at effective saturation is required to calculate the relative liquid water conductivity as $K_{l,rel} = K_l/K_{l,eff}$. As it wasn't measured, water uptake simulation was used to determine it. The water uptake test was simulated with values calculated with equation 12 and the $K_{l,eff}$ was adjusted until the simulation produced the measured A_w.

After that, the hygroscopic and overhygroscopic values were joined with linear interpolation. The following scaling term was used to modify the hygroscopic range (Scheffler 2010):

$$f_l(\Theta) = \frac{\Theta^{\eta_{sp}}}{\Theta^{\eta_{sp}} + (1-\Theta)^2 \cdot (1-\Theta^{\eta_{sp}})} \qquad (12)$$

Where	f_l	is moisture dependent factor [-]
	Θ	is defined as the ratio of moisture content and porosity, [m^3/m^3]
	η_{sp}	material dependent parameter [-]

In Delphin 5 the values of liquid water conductivity are fed to the program as relative values with respect to the liquid water conductivity at effective saturation and on a logarithmic scale.

$$\lg K_l(\Theta_l) = \log_{10}\big(f_l(\Theta_l) \cdot K_{rel}(\Theta_l)\big) \tag{13}$$

In Delphin 5 it is necessary to define sufficient amount of data points because of the way the program calculates the intermediate values. Wet-cup test simulations were used to adjust the liquid water conductivity function. Parameter η_{sp} was iteratively adjusted until the simulation produced the measured moisture flow.

The liquid water conductivity of the sheathing had a big impact on the simulation results. Larger conductivity values resulted in lower relative humidity values close to the sheathing. It was also noticed that the division of total moisture flow into vapor and capillary flux also affected the simulation results.

In the water uptake simulation the material was set 0.1 m thick and with width and depth of 1 m. As the moisture content of the material specimen was initially at a hygroscopic range the shape of the whole $K_l(\Theta_l)$ curve affected the results.

3. Results

During the calculations it was noticed that in some cases the use of non-capillary materials produced sufficiently good results. Besides the basic parameters the simulation results depended thus essentially on the moisture retention curve. This was the case for e.g. Wall 3b.

In all cases the direction of the moisture flow was from inside out. If the liquid water conductivity of the sheathing material was increased the values of relative humidity at the exterior surface of the insulation layer decreased. Because some cases didn't require the definition of the liquid water conductivity function these cases provided information of only the maximum values of liquid water conductivity.

Wall 12b shows an example of two different divisions of total moisture flow into vapor and liquid components.

In principle the cup test should include less error than the wall assembly test because of fewer factors involved. Despite of that wall 29b produced better results at wall assembly simulations if the liquid water conductivity of the sheathing at the hygroscopic range was larger than the values calculated from the cup tests.

If water vapor barrier is modeled as a contact resistance, it must be taken into account that the barrier acts as a water conduction barrier also. If the vapor barrier is included as a separate material layer, it can be set as a non-capillary material.

3.1 Calculation results

This chapter represents the calculated relative humidities at the exterior surface of the insulation layer compared to the measured ones. Temperatures or the relative humidity at the interior surface of the insulation layer are not represented here to save space and because they showed much less variation than the relative humidity at the exterior surface of insulation layer.

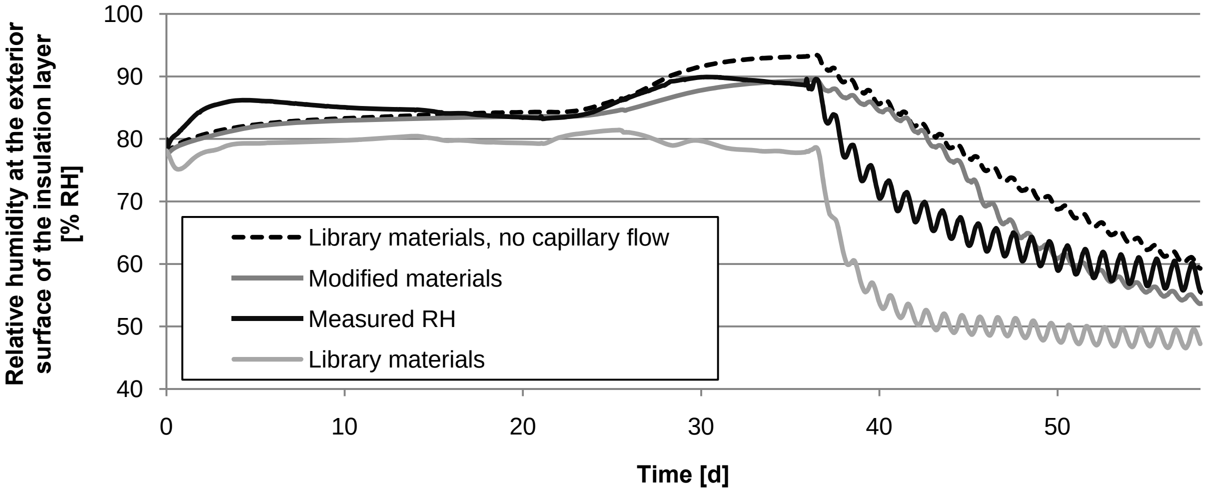

FIG (3). Wall 3b. Turning of capillary flow in library materials makes also the sheathing tighter and so the relative humidity rises in the insulation layer. With modified materials the liquid water conductivity is small but the rise in water content matches the moisture retention curve better. In sheathing the water vapor permeability is set constant in the hygroscopic range.

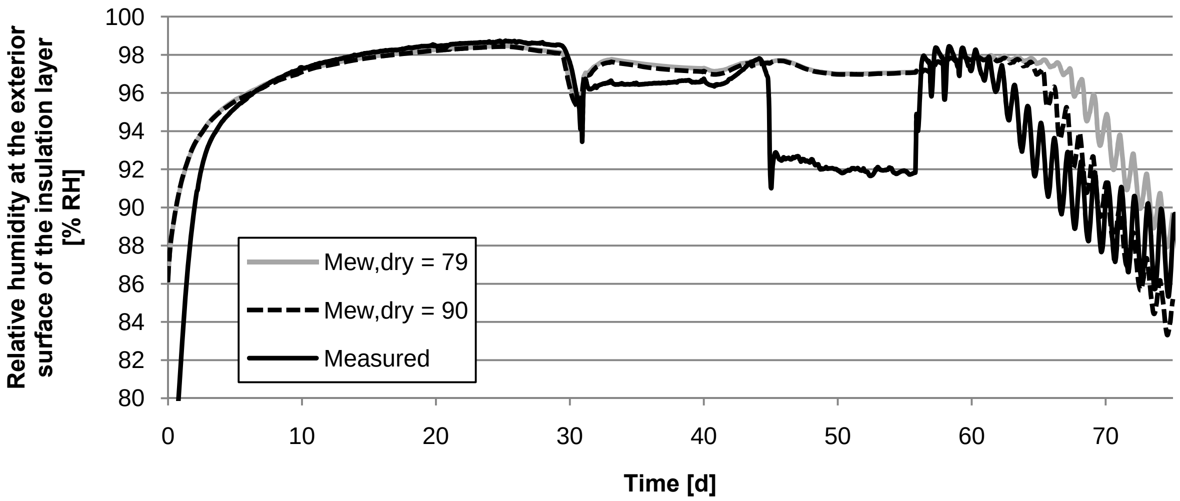

FIG (4). Wall 12b.Picture shows two simulated cases compared to the measured values. μ_{dry} = 79 is a results from the material tests at +23 °C. Curve of μ_{dry} = 90 is to represent the effect of separating the vapor and liquid water flows. Measured lower values at 45…55 days time are possibly due to moisture condensation at probes or similar.

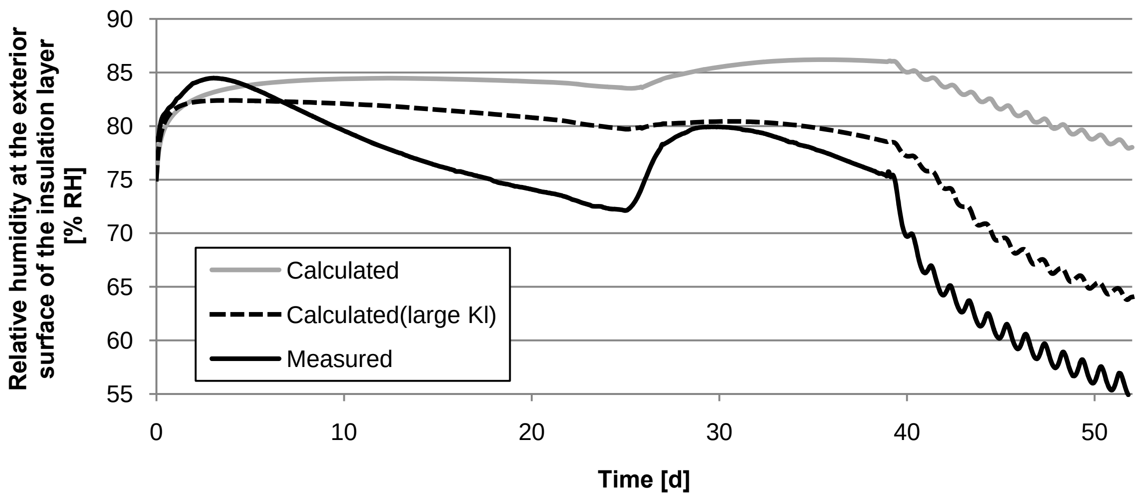

FIG (5). Wall 29b. Increasing the liquid water conductivity of the sheathing caused the relative humidity to decrease faster but with large values the material test simulations didn't correspond to measured values anymore. Reasons for this are discussed in the next chapter.

3.2 Sources of error

The whole chain from material tests to wall assembly tests and to simulation can include many different defects. Errors in wet cup tests would have a fundamental impact but on the other hand the results were in line with literature values. Of the used materials in wood hardboard, spruce plywood and pine timber the water vapor permeability changed in different temperatures when the measurements were made in temperatures of +23, +5 and -10 °C (Vinha 2005b). Error in the wet cup measurements might have caused differences but the temperature dependence might also have had an impact.

The liquid water conductivity or diffusivity was not measured but determined by simulating the water uptake experiment. Water absorption coefficient A_w alone might not describe the behavior of the material in the uptake test well enough (Scheffler 2008 p. 72).

The measured values of capillary saturation and water content during immersion were originally reported as water content per dry material volume. This produced large values for some wood-based materials and thus had to be adjusted based on literature values. On the other hand, moisture content in simulations stayed mostly in the hygroscopic range, in which the measured sorption isotherm values seemed reasonable.

Dividing the total moisture flow into vapor and liquid flows was also observed to have an effect on the calculation results. Including liquid water flow into the material models improved the calculation results. The division between vapor flow and liquid flow has probably also caused error.

In the water absorption experiment moisture content of material rises to the capillary saturation moisture content whereas the program uses the liquid water conductivity at effective moisture content. The drying experiment was not simulated because no reference data was available.

The selection of the monitoring point also affected the calculation results. In the insulation layer the relative humidity stays on a higher level closer to the sheathing than when the monitoring point is selected to be 6.5 mm inwards from the sheathing. The difference was approximately 1...3 %RH. The sinusoidal behavior of the relative humidity at the spring period has bigger amplitude closer to the sheathing than inside the insulation. Material specimens were held in known conditions before the wall assembly tests. However the initial moisture content might have changed during the test set up.

4. Conclusions

Wall assembly simulations with known boundary conditions were made with HAM-calculation program Delphin 5. Not all necessary material properties were measured for determining full range moisture retention curve and liquid water transfer function. For moisture retention curve the overhygroscopic values from suitable material in Delphin 5 material database were used. The liquid water conductivity function was determined from the moisture retention curve and adjusted with material test simulations.

Learning to use Delphin 5 had a good start and it will be used in the future. For the studied cases the program functioned correctly but more work is required for the authors to determine material properties for locally used building products. This is the case especially for wood-based products which are widely used in Finland.

For the case where wood fibreboard was used as sheathing the use of library material produced lower values of relative humidity than those measured. After the library material was adjusted with measured values, simulation results were closer to measured values.

Division of total moisture flow into vapor and liquid water phases was noticed to have an effect to the simulation results. Larger share of liquid water flow in the sheathing material caused the simulated relative humidity values to stay on a lower level at the exterior surface of the insulation layer.

5. Acknowledgements

The authors wish to thank all the friendly people at the Institute of Building Climatology at TU Dresden.

References

Airaksinen, M. 2003. Moisture and fungal spore transport in outdoor air-ventilated crawl spaces in a cold climate, Ph.D thesis. Espoo, Helsinki University of Technology, Department of Mechanical engineering. 66 p.

Grunewald, J., Häupl, P. & Bomberg, M. 2003. Towards An Engineering Model of Material Characteristics for Input to Ham Transport Simulations – Part 1: An Approach. Journal of Building Physics, Vol. 26, pp. 343--366.

Kalamees, T. & Kurnitski, J. 2010. Moisture Convection Performance of External Wall and Roofs. Journal of Building Physics, Vol. 33, pp. 225–247.

Kalamees, T. & Vinha, J. 2003. Hygrothermal calculations and laboratory tests on timber-framed wall structures. Building and Environment, Vol. 38, pp. 689–697.

Sasic Kalagasidis, A. 2004. HAM-Tools An Integrated Simulation Tool for Heat, Air and Moisture Transfer Analyses in Building Physics, Ph.D thesis. Gothenburg, Chalmers University of Technology, Department of Building Technology, Building Physics Division, 68 p.

Scheffler, G. 2008. Validation of hygrothermal material modeling under consideration of the hysteresis of moisture storage, Ph.D thesis. Dresden, Dresden University of Technology, Faculty of Civil Engineering, 236 p.

Scheffler, G. & Plagge, R. 2010. A whole range hygric material model: Modelling liquid and vapour transport properties in porous media. International Journal of Heat and Mass Transfer, Vol. 53, pp. 286 –296.

Vinha, J. 2007. Hygrothermal Performance of Timber-Framed External Walls in Finnish Climatic Conditions: A Method for Determining the Sufficient Water Vapour Resistance of the Interior Lining of a Wall Assembly, Ph.D thesis. Tampere, Tampere University of Technology, Laboratory of Structural Engineering, 338 p. + app. 10 p.

Vinha, J., Valovirta, I., Korpi, M., Mikkilä, A. & Käkelä, P. 2005b. Rakennusmateriaalien rakennusfysikaaliset ominaisuudet lämpötilan ja suhteellisen kosteuden funktiona. Tampere, Technical University of Tampere, Department of Civil Engineering, Publication 129. 101 p. + app. 211 p.