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Hygrothermal properties applied in numerical simulation: Interstitial condensation analysis

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ABSTRACT The problem of moisture damage in buildings has attracted interest from the early days of the last century, but it was only with the development of hygrothermal modelling that the general topic of moisture transport in buildings became the subject of more systematic study. Today, the evaluation of the risk of interstitial condensation in building envelope components can benefit from models of different complexity levels. This article starts with the analysis of the main material properties applied in the models that can tackle interstitial condensation, regarding standardization and experimental evaluation. Additionally, two commercial programmes that support two different levels of complexity of interstitial condensation analysis are compared: the more complex WUFI 4.2 and the simpler Condensa 13788. The comparison of both programmes uses a

brick wall with interior insulation. The results of this exercise allow for conclusions on the applicability of the models in view of material properties availability.

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INTRODUCTION

Building pathologies originated by moisture are frequently responsible for the degradation of building components and can affect users' health and comfort. The solutions for treating moisture-related pathologies are complex and, many times, of difficult implementation. Several of these pathologies are due to innovative techniques combined with new materials of poorly predicted performance. The knowledge of the physical processes that define hygrothermal behaviour allows for the prediction of a building response to climatic solicitation and for the selection of envelope solutions that will lead to required feasibility.

Interstitial condensation, originating undesired liquid water inside components, can lead to degradation of variable severity depending on the type of materials that are affected. This process depends on components characteristics and boundary conditions (interior and exterior).

Relevant standardization in the field of hygrothermal behaviour and energy performance is being developed by the International Organization for Standardization (ISO) and by the European Committee for Standardization (CEN), which established the technical committee CEN/TC 89 – Thermal Performance of Buildings and Building Components. This committee aims to study heat and moisture transfer and its effect on buildings' behaviour.

This article intends to evaluate, for the problem of interstitial condensation in building components, what is the structure of standardization for the available numerical simulation and connected experimental determination of material properties. Two numerical models of different complexity are then analysed using an example. The simpler model is supported by the software Condensa 13788 developed in collaboration with the Building Physics Laboratory – FEUP, based on the Glaser model, and it allows for analysis under steady state conditions. The more complex model is supported by the software WUFI 4.2 developed by the Fraunhofer Institute of Building Physics, allows for analysis under transient conditions.

HYGROTHERMAL SIMULATION

A research, at the end of 2007, found 57 existing hygrothermal simulation models that can be applied in the analysis of interstitial condensation in building components (US Department of Energy Webpage, 2008). The majority has the capacity of analysing transient conditions problems. Modelling physical transport processes implies a certain degree of simplifications of reality; depending on how detailed the solution is intended.

The model used by WUFI 4.2 is based on the standard CEN, EN 15026 (2007). It allows for a detailed knowledge of the hygrothermal state of the building component. It is possible to evaluate, for the simulation period, the hourly evolution of the component's total moisture content. The variation of the moisture content, temperature and relative humidity for each layer or for a chosen location in the component is also available, not only through the simulation period, but also for the component profile for a specific point in time. Although its complexity, the model neglects: (a) convective transport (heat and moisture); (b) some of the liquid transport mechanisms, as seepage flow through

gravitation, hydraulic flow through pressure differentials and electrokinetic and osmotic effects; (c) the interdependence of salt and water transport; (d) the resistance of the interface between two capillary-active materials; (e) the enthalpy flows resulting from the transport of liquid water due to temperature differential. The material properties required by this software are bulk density, porosity, specific heat capacity of dry material, moisture storage function, liquid transport coefficient (suction and redistribution), moisture-dependent thermal conductivity and moisture-dependent vapour diffusion resistance.

The software Condensa 13788 applies the model defined by the standard CEN, EN ISO 13788 (2002), allowing for the calculation of temperature, vapour pressure and saturation pressure in defined interfaces of a component, for monthly periods. The Glaser model simplifies the heat and moisture transport process assuming: (a) condensation only occurs in interfaces and there is no redistribution of liquid water; (b) the dependence of thermal conductivity on moisture content is negligible; (c) capillary suction and liquid moisture transfer are negligible; (d) the heat and moisture transport by convection are neglected; (e) one-dimensional moisture transfer is assumed; (f) boundary conditions are constant over the months (average value); (g) the effects of solar and long-wave radiation and precipitation are neglected. The material properties required by this software are thermal conductivity and vapour permeability.

MATERIAL PROPERTIES

Bulk density (ρ)

Several standards can be applied for the experimental determination of this property, as CEN, EN ISO 10545-3 (1995) (ceramic tiles), BS, EN 12390-7 (2000) (concrete), BS, EN 772-13 (2000) (masonry units). The samples must be dried until constant mass is reached. The samples' volume is calculated based on the average of three measurements of each dimension.

Bulk porosity (ε)

The standards CEN, EN ISO 10545-3 (1995) (ceramic tiles) and ASTM, C 20 (2000) (fired white ware products) could be used to measure the bulk porosity of building materials. The samples are dried until constant mass is reached (m_1). After a period of stabilization, the samples are kept immersed under constant pressure. Weigh the immersed sample (m_2) and the emerged sample (m_3), the bulk porosity is given by: $\varepsilon = (m_3 - m_1) / (m_3 - m_2)$.

Specific heat capacity (c_p)

This test method employs the classical method of mixtures to cover the determination of mean specific heat of thermal insulating materials. The materials must be essentially homogeneous and composed of matter in the solid state (see standard ASTM, C 351-92b (1999)).

The test procedure provides for a mean temperature of approximately 60°C (100–20°C; temperature range), using water as the calorimetric fluid. By substituting other calorimetric fluids, the temperature range may be changed as desired. All the samples shall be dried to constant mass in an oven at a temperature of 102–120°C, and the method is to add a measured material mass, at high temperature, to a measured water mass at low temperature in order to determine the resulting equilibrium temperature. The heat absorbed by water and container is so calculated, and this value equalized to the amount of heat released expression in order to calculate the specific heat desired.

Thermal conductivity (λ)

The standards CEN, EN ISO 8302 (1991); BS, EN 12664 (2001); BS, EN 12667 (2001); and BS, EN 12939 (2001) can be applied to determine the thermal conductivity of building materials using the Guarded Hot Plate method. The method uses two identical samples of parallel faces. After the system stabilization, a constant flux is obtained, perpendicular to the samples' dominant faces. Knowing the temperature in opposite faces allows determining the thermal conductivity of the samples.

Moisture storage functions

The sorption curve of a material can be determined using different methods. Gravimetric type methods are usually preferred for building materials following, for instance, the standard CEN, EN ISO 12571 (2000). According to this document, the sorption curves are determined by stabilizing material samples in different conditions of relative humidity and constant temperature. The obtained values allow knowing the moisture content of the material at hygroscopic equilibrium with the surrounding air.

The moisture content in the over-hygroscopic region is usually defined using suction curves that can be determined using pressure plate measurements.

Water vapour permeability (δ_p)

Vapour permeability is usually determined using the cup test method. The sample is sealed in a cup containing either a desiccant (dry cup) or a saturated salt solution (wet cup). The set is put inside a climatic chamber where the relative humidity value is regulated to be different from the one inside the cup. The vapour pressure gradient originates a vapour flux through the sample. The standard CEN, EN ISO 12572 (2001) can be used as a reference.

Water absorption coefficient (A)

The standard CEN, EN ISO 15148 (2002) can be applied in the determination of the water absorption coefficient by partial immersion. The side faces of the samples are made impermeable to obtain a directional flux. After stabilization with the room air, the samples' bottom faces are immersed (5 ± 2 mm). The samples are then weighed at time intervals defined according to a log scale during the first 24-h period and after that every 24 h. This property is derived from the linear relation between mass variation and the square root of time. When that relation is not verified, only the values registered at 24 h are used.

The liquid conductivity, K , can be related to the moisture diffusivity, D_w , and is highly dependent on moisture content. This implicates that its determination implies the knowledge of moisture content profiles on the material. These profiles can be estimated from the water absorption coefficient.

Reference values

The standards CEN, EN ISO 10456 (2007) and BS, EN 12524 (2000) present tabulated design values of hygrothermal properties for a wide range of building materials (see Table 1).

Table 1: Example of material properties' values

Materials	ρ kg/m ³	ε (%)	c_p J/(kgK)	λ W/(mK)	$\delta_p \times 10^{12}$ kg/(msPa)	A kg/(m ² s ^{0.5})
Stone	1600–2800	0.5–20	1000	0.5–3.5	2.0	0.01–0.025
Lime plaster	1600	26	1000	0.8–1.5	4.5–13	0.01–0.25
Concrete	2000–2400	16	1000	1.15–2.0	0.7–13	0.01
Brick	1000–2400	28	920	0.34–1.04	2.4	0.05

CASE STUDY – INTERSTITIAL CONDENSATIONS ON FAÇADES

Hygrothermal modelling offers a powerful tool for predicting heat and moisture transport through multilayer building assemblies. In this study, two hygrothermal models, WUFI 4.2 and Condensa 13788, were used to compare the results of interstitial condensation on façades.

Figures 1 and 2 show a schematic representation of the façade under study and the internal and external boundary conditions used in this application, respectively.

Simulation with Condensa 13788

Condensa 13788 allows the risk assessment for interstitial condensation according to the standard CEN, EN ISO 13788 (2002). The material properties (see Table 2) necessary for the simulation with Condensa 13788 are the thermal conductivity (λ) and the water vapour diffusion resistance factor (μ), derived from vapour permeability.

Condensa 13788 assumed one-dimensional, steady-state conditions. Moisture transfer is assumed to be pure water vapour diffusion, described by the following equation,

$$g = \frac{\delta_a}{\mu} \cdot \frac{\Delta P}{\Delta x} = \delta_a \frac{\Delta P}{s_d} \quad (1)$$

Figure 1: Building component under study – exterior wall with interior insulation.

Figure 2: Boundary condition for simulation.

Table 2: Material properties required by Condensa 13788

Materials	d (m)	λ (W/(mK))	μ (-)
Exterior rendering	0.02	1.2	25
Brick wall	0.2	0.6	10
Mineral insulation board	0.08	0.043	3.4
Gypsum board	0.0125	0.2	8.3

where s_d is the water vapour diffusion-equivalent air layer thickness, δ_a is the water vapour permeability of air with respect to partial vapour pressure, $\delta_a = 2 \times 10^{-10}$ kg/(m.s.Pa) and P is the water vapour pressure. The density of heat flow rate is given by,

$$q = \lambda \frac{\Delta T}{d} = \frac{\Delta T}{R} \quad (2)$$

where T is the temperature in Celsius, R is the thermal resistance and d is the material layer thickness.

Figure 3 presents an example of Condensa 13788 graphical output indicating the interface where condensation/drying occur for each month. Table 3 presents the simulation results, where gc_1 represents the flux of condensation/drying for each month and Ma_1 stands for the amount of water resulting from accumulated condensation/drying on the interface. The results indicate that the wall would go back to dry state in an annual cycle. With the information from Ma_1 , it would also be possible to determine whether the condensed flux would originate pathologies in the wall layers. However, that evaluation is not simple since the actual amount of water in each layer next to the condensation interface is unknown. This aspect can lead a designer to be too conservative and adopt a strategy of full elimination of condensation risk.

Simulation with WUFI 4.2

The WUFI 4.2 allows realistic calculation of the transient hygrothermal behaviour of multilayer building components exposed to natural climate conditions (Kuenzel and Kiessl, 1996). This programme is a one-dimensional model for heat and moisture transport analysis of building envelope components, based on the finite volume method.

The governing equations for moisture and energy transfer are, respectively,

$$\frac{\partial w}{\partial \varphi} \frac{\partial \varphi}{\partial t} = \nabla (D_\varphi \nabla \varphi + \delta_p \nabla (\varphi p_{\text{sat}})) \quad (3)$$

$$\frac{\partial H}{\partial T} \frac{\partial T}{\partial t} = \nabla (\lambda \nabla T) + h_v \nabla (\delta_p \nabla (\varphi p_{\text{sat}})) \quad (4)$$

where w is water content (kg/m³), φ is the relative humidity (per cent), t is the time (s), D_φ is the liquid conduction coefficient (kg/ms), δ_p is the vapour permeability (kg/m.s.Pa),

Figure 3: Condensa 13788 graphical output.

Table 3: Condensa 13788 simulation results

Month	Time (h)	θ_e (°C)	φ_e (%)	P_e (Pa)	θ_i (°C)	$\ddot{A}_v$ (g/m ³)	P_i (Pa)	gc_1 (kg/(m ² s))	Ma_1 (kg/m ²)
October	744	16.2	80	1472.50	20.0	5	2145.29	1.96E-07	0.5242
November	720	12.3	81	1158.12	20.0	5	1826.40	2.48E-07	1.1659
December	744	9.9	81	987.48	20.0	5	1652.99	2.69E-07	1.8876
January	744	9.3	81	948.44	20.0	5	1613.26	2.75E-07	2.6243
February	672	10.1	80	988.45	20.0	5	1654.19	2.55E-07	3.2405
March	744	11.5	75	1017.19	20.0	5	1684.55	1.70E-07	3.6956
April	720	12.9	74	1100.52	20.0	5	1769.50	1.34E-07	4.0422
May	744	15.1	74	1269.40	22.0	5	1943.23	6.58E-08	4.2185
June	720	18.1	74	1536.12	24.0	0	1536.12	-6.81E-07	2.4526
July	744	19.9	73	1695.44	24.0	0	1695.44	-7.44E-07	0.4597
August	744	19.8	73	1684.97	24.0	0	1684.97	-7.42E-07	0
September	720	19.0	76	1669.08	22.0	0	1669.08	0.00E+00	0

p_{sat} is the saturation vapour pressure (Pa), H is the enthalpy (J/m³), T is the temperature in Kelvin and h_v is the latent heat of phase change (J/kg). The water vapour diffusion resistance factor, μ , used by WUFI is given by,

$$\mu = \frac{\delta_a}{\delta_p} = \frac{2.0 \times 10^{-7} T^{0.81} / P_n}{\delta_p} \quad (5)$$

where P_n is the normal atmospheric pressure (Pa).

European standard CEN, EN 15026 (2007) provides minimum criteria for simulation software used to predict one-dimensional transient heat and moisture transfer in multilayer building components exposed to transient climate conditions on both sides, and WUFI 4.2 complies with all requirements of this European standard. WUFI programme requirements of material properties include (see Figure 4) bulk density (kg/m³), porosity (m³/m³), heat capacity (J/kgK), water content (kg/m³) versus relative humidity, liquid transport coefficient (suction and redistribution) (m²/s) versus water content (kg/m³), heat conductivity (W/mK) versus water content (kg/m³) and diffusion resistance factor versus relative humidity (per cent).

The application of WUFI 4.2 in the case study provides the variation with time of the moisture content in the building element and in each layer (see Figure 5). It is also possible to know the moisture content profile at a given point in time (see Figure 6).

Layer/Material Data

Layer/Material Name: Mineral Insulation Board

Material Data | Info Text

Basic Values	
Bulk density [kg/m ³]	115,0
Porosity [m ² /m ³]	0,95
Specific Heat Capacity, Dry [J/kgK]	850,0
Thermal Conductivity, Dry [W/mK]	0,043
Water Vapour Diffusion Resistance Factor [-]	3,4

Hygic Extensions

Moisture Storage Function

Liquid Transport Coefficient, Suction

Liquid Transport Coefficient, Redistribution

Thermal Conductivity, moisture-dependent

Water Vapour Diffusion Resistance Factor, moisture-dependent

Graph | Edit Table | from File...

Water Content [kg/m³]

Relative Humidity [-]

Approximation Parameter

Moisture-dep. Thermal Cond. Supplement [%/M.-%] 3,7

Typical Built-In Moisture [kg/m³] 4,5

Color Layer thickness [m] 0,08

Paste into Material Database

OK Abort Help

Figure 4: Material properties required by WUFI 4.2.

Figure 5: Component moisture content variation over time in WUFI 4.2 simulation.

Figure 6: Component moisture content profiles in WUFI 4.2 simulation.

DISCUSSION

Using two simulation programmes of different complexity degree allows for the following discussion:

- The application of Condensa 13788 is less demanding regarding material properties. Admitting steady-state condition, moisture retention curves are not necessary. It must

Figure 7: Thermal conductivity variation over time in WUFI 4.2 simulation.

be understood that if properties must be introduced in a model as moisture dependent, the data availability decreases. Characterization of moisture dependency properties is of slow and complex experimental determination and is not easy to find in literature for all materials.

- Results interpretation, in the case of Condensa 13788 demand less basic building physics knowledge to perform interstitial condensation risk assessment.
- The results from WUFI 4.2 allow for extensive knowledge on each layer's moisture content development over time. This type of information is important for component optimization as it supports a detailed risk control strategy. As an example, it is possible to evaluate the increase of thermal conductivity of the mineral wool layer, due to the increase in moisture content during winter.
- Both programmes indicated that, for the case study, interstitial condensation or the increase in moisture content would not cause severe damage, as the component would regain equilibrium during summer. But, the more detailed simulation pointed out the decrease of insulating capacity during winter (see Figure 7). This is due to the moisture content increase in mineral wool, which implies an increase of thermal conductivity.

CONCLUSIONS

This article presented an overview of hygrothermal properties commonly used in numerical simulation and methods that allow for their determination. That overview demonstrated all the properties can be experimentally determined or derived from connected experiments. Moreover, existing standards support most of the necessary experimental procedures.

Hygrothermal simulation can be implemented with different complexity degrees. An important difference between models is the ability to tackle transient behaviour, since steady-state conditions will frequently be a rough approximation to reality. Standardization also supports hygrothermal simulation contributing to higher feasibility on model application by designers.

A case study of interstitial condensation risk assessment allowed for comparison between two different complexity models. Although more advanced models are a better support for component optimization, they are more demanding regarding user ability to interpret results and material data availability. If a designer is defining, for instance, a solution for improving the thermal resistance of an existing building element, he must therefore decide which type of modelling should be applied to solve a specific problem.

A possible approach could be to start with the simpler model and evaluate whether the intended solution has any risk of interstitial condensation. This first approach should be developed on the safe side, using worst case scenario boundary conditions. If risk of condensation is detected and cost optimization is relevant, more complex modelling can be produced, allowing, for instance, for a suitable design of a vapour barrier.

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