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Hygrothermal Numerical Simulation: Application in Moisture Damage Prevention

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1. Introduction

1.1 Background

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.

Over the last five decades, hundreds of building energy software tools have been developed or enhanced to be used. A list of such tools can be obtained in the US Department of Energy Webpage (2007). This directory provides information for more than 345 building software tools for evaluating energy efficiency, renewable energy and sustainability in buildings.

The problem of moisture damage in buildings has attracted interest from the early days of the last century, but it was during the past decades that the general topic of moisture transport in buildings became the subject of more systematic study, namely with the development of the modelling hygrothermal performance. In the field of building physics the hygrothermal models are widely used to simulate the coupled transport processes of heat and moisture for one or multidimensional cases. The models may take into account a single component of the building envelope in detail or a multizonal building.

In literature, there are many computer-based tools for the prediction of the hygrothermal performance of buildings. These models vary significantly concerning their mathematical sophistication and, as shown Straube and Burnett (1991), this sophistication depends on the degree to which the model takes into consideration the following parameters: moisture transfer dimension; type of flow (steady-state, quasi-static or dynamic); quality and availability of information and stochastic nature of various data (material properties, weather, construction quality, etc.).

All the hygrothermal simulation tools presented later in this paper are based on one of the following numerical methods for space and time discretization:

a. Finite Difference Methods (FDM) and Finite Control Volume (FCV) methods;
b. Finite Element Method (FEM);
c. Response Factor and Transfer Function method.

1.2 HAM models

Different models for the coupled heat, air, moisture and salt transport have been developed and incorporated into various software programs used in the field of porous building materials and in the closely related field of wetting and drying of soils.

The HAM models (heat, air and moisture) combine the flow equations with the mass and energy balances. Transient, one-dimensional models for combined heat, air and moisture transport in building components have been reasonably well established for about two decades now. In 1996 the final report of Volume 1 – Modelling, of the Annex 24 of the International Energy Agency (IEA), elaborated by Hens (1996), showed that 37 programs had been developed by researchers of 12 countries, 26 of which were non-steady sate models. In the last ten years, many programs indicated in this work have developed new versions and improved the conditions of analysis and therefore sensitized the values of results.

More recently, a review of hygrothermal models for building envelope retrofit analysis made by Canada Mortgage and Housing Corporation (2003) has identified 45 hygrothermal modelling tools, and in the last four years, 12 new hygrothermal models were developed, most of them during Annex 41 (Rode and Grau, 2004).

Most of the 57 hygrothermal models available in literature are not readily available to the public outside of the organization where they were developed. In fact, only the following 14 hygrothermal modelling tools are available to the public in general. The programs available for the public in general were analyzed in detail (Delgado *et al.* (2010)), namely the input of material properties and the boundary conditions (inside and outside).

1D-HAM - a one-dimensional model for heat, air and moisture transport in a multi-layered porous wall. The program uses a finite-difference solution with explicit forward differences in time. Analytical solutions for the coupling between the computational cells for a given air flow through the construction are used. The moisture transfer model accounts for diffusion and convection in vapour phase, but not liquid water transport. Heat transfer occurs by conduction, convection and latent heat effects. Climatic data are supplied through a data file with a maximum resolution of values per hour over the year. The program accounts for surface absorption of solar radiation (Hagentoft and Blomberg, 2000).

BSim2000 - a one-dimensional model for transport of heat and moisture in porous building materials. BSim2000, the successor of the MATCH program, is a computational design tool for analysis of indoor climate, energy consumption and daylight performance of building. The software can represent a multi-zone building with heat gains, solar radiation through windows, heating, cooling, ventilation and infiltration, steady state moisture balance, condensation risks. A new transient moisture model for the whole building was also developed as an extension of BSim2000. One of the limitations is that liquid moisture transfer in constructions is not yet represented (Rode and Grau, 2004).

DELPHIN 5 - a one or two-dimensional model for transport of heat, air, moisture, pollutant and salt transport in porous building materials, assemblies of such materials and building envelopes in general. The Delphin program can be used in order to simulate transient mass and energy transport processes for arbitrary standard and natural climatic boundary conditions (temperature, relative humidity, driving rain, wind speed, wind direction, short and long wave radiation).This simulation tool is used for:

a. Calculation of thermal bridges including evaluation of hygrothermal problem areas (surface condensation, interstitial condensation);

b. Design and evaluation of inside insulation systems;
c. Evaluation of ventilated facade systems, ventilated roofs;
d. Transient calculation of annual heating energy demand (under consideration of moisture dependent thermal conductivity);
e. Drying problems (basements, construction moisture, flood, etc);
f. Calculation of mold growth risks and further applications.

A large number of variables as moisture contents, air pressures, salt concentrations, temperatures, diffusive and advective fluxes of liquid water, water vapour, air, salt, heat and enthalpy which characterize the hygrothermal state of building constructions, can be obtained as functions of space and time (Nicolai, Grunewald and Zhang, 2007).

EMPTIED - a one-dimensional model for heat, air and moisture transport, with some considerations for air leakage included (Rousseau, 1999). The software makes enough simplifying assumptions to be practical for designers to use in order to compare the relative effects of different climates, indoor conditions, wall materials and air tightness on wall performance. EMPTIED calculates temperatures assuming steady-state conditions for the duration of each bin, neglecting latent heat and heat transported by moving air. The program uses monthly bin temperature data and outputs plots of the monthly amount of condensation, drainage and evaporation. It is recommended for simple analysis of air leakage. EMPTIED has limitations that should be kept in mind. Initial moisture contents cannot be specified. Wind, sun and rain are not taken into account. Air movement is taken to be the same through every layer, there are no convection loops within layers or between the exterior and vented cavities. The maximum amount of moisture a material can store safely is assumed to be the same amount at which condensation will start to occur on the surface.

GLASTA - a one-dimensional model for heat and moisture transport in porous media. It is based on the Glaser method, but includes a model for capillary distribution within the layers of the assembly and may be suitable for assessing drying potential. The program calculates monthly mean values of temperature and vapour pressure or relative humidity and climatic database for more than 100 European locations are presented (see Physibel, 2007).

hygIRC-1D - a one-dimensional simulation tool for modelling heat, air and moisture movement in exterior walls. This program is an advanced hygrothermal model that is an enhanced version of the LATENITE model developed jointly by Institute for Research in Construction and the VTT (Finland). The hygIRC program can be used to model common wall systems. The hygIRC model simulates heat, air and moisture conditions within the retrofitted walls to determine how the retrofits affect the durability of the wall system. This information can be used as a means to confirm the integrity of several specific retrofit measures developed for high-rise wall structures before they are recommended to the building industry (Karagiosis, 1993 and Djebbar *et al*., 2002a,b).

HAMLab - a one-dimensional heat, air and moisture simulation model. This hygrothermal model is a collection of four tools and functions in the MatLab/Simulink/FemLab environment that includes: HAMBASE (used for: indoor climate design of multizone buildings; energy and (de)humidification simulation; rapid prototyping; and HAM building model component to be used with HAMSYS, for the design of HVAC systems), HAMSYS (used for: HVAC equipment design; and controller design), HAMDET (used for: HAM simulation of, up to 3D, building constructions; and airflow simulation in rooms and around buildings) and HAMOP (used for: design parameters optimization; and optimal operation). All tools have been validated, except HAMOP, by comparison with experimental data obtained in the laboratory and in field studies (van Schijndel, 2005).

The main objective of HAMBASE is the simulation of the thermal and hygric indoor climate and energy consumption. In SimuLink, the HAMBASE model is visualised by a single block with input and output connections. The interface variables are the input signal of the HAMBASE SimuLink model and the output signal contains for each zone the mean comfort temperature, the mean air temperature and RH. In HAMBASE model the diffusion equations for heat and moisture transfer in the walls are modelled with a finite difference scheme and solved with an implicit method.

HAM-Tools - a one-dimensional heat, air and moisture transfer simulation model. The main objective of this tool is to obtain simulations of transfer processes related to building physics, i.e. heat and mass transport in buildings and building components in operating conditions. Using the graphical programming language Simulink and Matlab numerical solvers, the code is developed as a library of predefined calculation procedures (modules) where each supports the calculation of the HAM transfer processes in a building part or an interacting system. Simulation modules are grouped according to their functionality into five sub-systems: Constructions, Zones, Systems, Helpers and Gains (Kalagasidis, 2004). The software is an open source, new modules can be easily added by users and moreover they are free of charge and can be downloaded from the internet.

IDA-ICE - a tool for building simulation of energy consumption, indoor air quality and thermal comfort. It covers a large range of phenomena, such as the integrated airflow network and thermal models, CO_2 and moisture calculation and vertical temperature gradients. For example, wind and buoyancy driven airflows through leaks and openings are taken into account via a fully integrated airflow network model. IDA ICE may be used for the most building types for the calculation of:

a. The full zone heat and moisture balance, including specific contributions from: sun, occupants, equipment, lighting, ventilation, heating and cooling devices, surface transmissions, air leakage, cold bridges and furniture;
b. The solar influx through windows with a full 3D account of the local shading devices and those of surrounding buildings and other objects;
c. Air and surface temperatures;
d. The operating temperature at multiple arbitrary occupant locations, e.g. in the proximity of hot or cold surfaces. The full non-linear Stephan-Bolzmann radiation with the view factors is used to calculate the radiation exchange between surfaces;
e. The directed operating temperature for the estimation of asymmetric comfort conditions;
f. Comfort indices, PPD and PMV, at multiple arbitrary occupant locations;
g. The daylight level at an arbitrary room location;
h. The air, CO_2 and moisture levels, which both can be used for controlling the VAV (Variable Air Volume) system air flow;
i. The air temperature stratification in displacement ventilation systems;
j. Wind and buoyancy driven airflows through leaks and openings via a fully integrated airflow network model. This enables one to study temporarily open windows or doors between rooms;
k. The airflow, temperature, moisture, CO_2 and the pressure at arbitrary locations of the air-handling and distribution systems;
l. The power levels for primary and secondary system components;
m. The total energy cost based on time-dependent prices.

To calculate moisture transfer in IDA-ICE, the common wall model RCWall should be replaced with HAMWall, developed by Kurnitski and Vuolle (2000). It can be used either as a single independent model or as a component of a bigger system. HAMWall model can be used also as a single program. The moisture transfer is modelled by one moisture-transfer potential, the humidity by volume. The liquid water transport is not modelled and hysteresis is not taken into account. By using this moisture transfer model it is possible to study the following cases:

a. The effect of structures on the indoor air quality and thermal comfort;
b. The effect of moisture buffering building materials and furniture to dampen the fluctuation of air humidity;
c. Making the hygrothermal analysis by taking into account the changes in the indoor climate;
d. To study the influence of the ventilation system caused under or over pressure on the hygrothermal conditions in the building envelope;
e. To study the influence of moisture on the heating and cooling load and on the performance of heating and cooling equipment.

MATCH - a one-dimensional model for heat and moisture transport in composite building structures. A modified version of the program also calculates air flow (Rode, 1990). The program uses both the sorption and suction curves to define the moisture storage function and the sorption isotherm in the hygroscopic regime. MATCH uses a Finite Control Volume method to calculate the transient evolution of both the thermal and the moisture related variables, and the moisture transport is assumed to be by vapour flow only, defined by the vapour permeability of the material. In the capillary regime the suction curve is used together with the hydraulic conductivity to model moisture transport. Some applications of the program are:

a. Determining of moisture transport in and through building constructions;
b. Calculating the temperature and moisture profiles transiently by considering the thermal and hygroscopic capacities.

By dividing the time into small steps, it is possible to take into account the effect on constructions of short, intensive temperature gradients, such as when they are exposed to solar radiation. MATCH can be used successfully for the analysis and design of protected membrane roofs and walls with non-absorbent cladding. The program has been validated by comparison with experimental data obtained in the laboratory and in field studies.

MOIST - a one-dimensional model for heat and moisture transport in building envelopes. It models moisture transfer by diffusion and capillary flow, and air transfer by including cavities that can be linked to indoor and outdoor air (Burch and Chi, 1997). The program enables the user to define a wall, cathedral ceiling or low-slope roof construction, and to investigate the effects of various parameters on the moisture accumulation within layers of the construction, as a function of time of year for a selected climate. Most of the material data required by the program are coefficients of curve-fits to specific equations for each property. The equilibrium moisture curves had to be severely approximated, close to the saturation point. Some applications of the MOIST program are:

a. Predicting the winter moisture content in exterior construction layers;
b. Predicting the surface relative humidity at the construction layers in hot and humid climates, thereby analysing the potential for mould and mildew growth;
c. Determining the drying rates for materials containing original construction moisture;

d. Investigating the performance of cold refrigeration storage rooms;
e. Analysing the effect of moisture on heat transfer.

Finally, MOIST is a one-dimensional model, doesn't include exterior wetting of a construction by rain and the insulating effect and change in roof absorptance from a snow load. Moreover, the model does not include heat and moisture transfer by air movement (the construction is assumed to be air tight) and the weather data for European cities are not available and cannot be generated (only has weather data of USA and Canada).

MOISTURE-EXPERT - one or two-dimensional model for heat, air and moisture transport in building envelope systems (Karagiozis, 2001). The program is, basically, software developed by Oak Ridge National Laboratory and Fraunhofer Institute for Building Physics, to adapt the original European version of WUFI software for USA and Canada. The model treats vapour and liquid transport separately. The moisture transport potentials are vapour pressure and relative humidity, and the energy transport potential is the temperature. The model includes the capability of handling temperature dependent sorption isotherms and liquid transport properties as a function of drying or wetting processes. It is a highly complex program, typically requiring more than 1000 inputs for the one-dimensional simulations. Inputs include: exterior environmental loads, interior environmental loads, material properties and envelope system and subsystem characteristics.

UMIDUS - a one-dimensional model for heat and moisture transport within porous media, in order to analyze hygrothemal performance of building elements when subjected to any kind of climate conditions (Mendes et al., 1999). Diffusion and capillary regimes are modelled, so moisture transport occurs in the vapour and liquid phases. The model predicts moisture and temperature profiles within multi-layer walls and low-slope roofs for any time step and calculates heat and mass transfer. The program needs to be validated.

WUFI - a one or two-dimensional model for heat and moisture transport developed by Fraunhofer Institute in Building Physics (IBP). It was validated using data derived from outdoor and laboratory tests, allows calculation of the transient hygrothermal behaviour of multi-layer building components exposed to natural climate conditions (Kuenzel and Kiessl, 1997). Heat transfer occurs by conduction, enthalpy flow (including phase change), short-wave solar radiation and long-wave radiative cooling (at night). Convective heat and mass transfer is not modelled. Vapour-phase transport is by vapour diffusion and solution diffusion, and liquid-phase water transport is by capillary and surface diffusion.

As the purpose of most hygrothermal models is usually to provide sufficient and appropriate information needed for decision-making, four items should be considered when choosing software for modelling a single component of the building envelope or a multizonal building:

a. The software must be in the public domain (freeware or commercially) available;
b. Suitability of the software for the single component or a multizonal building analysis under consideration must be assured;
c. The programs must be of reasonably recent vintage or with recent further development;
d. The software must be "user friendly".

Finally, as the programs have different hygrothermal potentialities, strengths and weaknesses, such as the ability to model heat and moisture transfer by air movement, 2-D or 3-D phenomena, or the capability to simulate high number of zones in a reasonable execution time, the investigators need to select the hygrothermal simulation tools that suit better to their problems.

1.3 Numerical simulations data

The hyrothermal performance of a building can be assessed by analysing energy, moisture and air balances. The hygrothermal balances consider the normal flows of heat by conduction, convection and radiation; moisture flows by vapour diffusion, convection and liquid transport; and airflows driven by natural, external or mechanical forces.

The prediction of the hygrothermal performance of the building enclosure typically requires some knowledge of:

Geometry of the enclosure - The enclosure geometry must be modelled before any hygrothermal analysis can begin. In simple methods the geometry is reduced to a series of one-dimensional layers. The enclosure geometry includes all macro building details, enclosure assembly details and micro-details.

Material Properties - Material properties and their variation with temperature, moisture content and age, as well as their chemical interaction with other materials are also critical. Some material properties needed in hygrothermal simulation are: bulk density, porosity, specific heat capacity, thermal conductivity, sorption isotherm, vapour permeability and diffusivity, suction pressure, liquid diffusivity, specific moisture capacity, etc.

Boundary Conditions - The boundary conditions imposed on a mathematical model are often as critical to its accuracy as the proper modelling of the moisture physics. In general, the following environment needs to be known: (i) interior environment, including the interaction of the enclosure with the interior environment; (ii) exterior environment, including the interaction of the building with the exterior environment and (iii) boundary conditions between elements. The correct treatment of the interfacial flows at boundaries between control volumes of different type is an important point in successful modelling.

1.3.1 Material properties

Bulk density (ρ) - Several standards can be applied for the experimental determination of this property, as EN ISO 10545-3 (1995) for ceramic tiles, EN 12390-7 (2000) for concrete, EN 772-13 (2000) for 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 EN ISO 10545-3 (1995) for ceramic tiles and ASTM C 20 (2000) for 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 of 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 ASTM C 351-92b (1999)).

The test procedure provides for a mean temperature of approximately 60°C (100 to 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 to 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 equalised to the amount of heat released expression in order to calculate the specific heat desired.

Thermal conductivity (λ) - The standards ISO 8302 (1991), EN 12664 (2001), EN 12667 (2001) and 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 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 EN ISO 12572 (2001) can be used as a reference.

Water absorption coefficient (A) - The standard 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) and 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 EN ISO 10456 (2007) and EN 12524 (2000) present tabulated design values of hygrothermal properties for a wide range of building materials (see Table 1).

Materials	ρ **kg/m³**	ε **(%)**	c_p **J/(kgK)**	λ **W/(mK)**	$\delta_p \times 10^{12}$ **kg/(msPa)**	A **kg/(m²s$^{0.5}$)**
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

Table 1. Example of material properties values.

1.3.2 Boundary conditions

A critical aspect in the design of envelope elements is the inclusion of the exterior and interior hygrothermal environmental loads (see Table 2). The most important exterior environmental loads are: (1) ambient temperature; (2) ambient relative humidity; (3) diffuse solar radiation; (4) direct solar radiation; (5) cloud index; (6) wind speed; (7) wind direction and (8) horizontal rain.

Name	Type	Boundary Conditions (outside)										B.C. (inside)			
		1	2	3	4	5	6	7	8	9	10	A	B	C	D
1D-HAM	1D-HAM	X	X	X	X				X			X	X		
BSim2000	1D-HM	X	X	X	X	X	X		X	X		X	X	X	
DELPHIN 5	1/2D-HAMPS	X	X	X	X	X	X	X	X			X	X	X	
EMPTIED	1D-HAM	X	X	X								X	X	X	
GLASTA	1D-HM	X	X		X				X			X			
hygIRC-1D	1D-HAM	X	X		X	X	X	X		X	X	X	X		X
HAMLab	1D-HAM	X	X			X	X		X	X		X	X		
HAM-Tools	1D-HAM	X	X	X	X	X	X	X	X	X		X	X	X	
IDA-ICE(*)	1D-HAM	X	X	X	X	X	X		X			X	X		
MATCH	1D-HAM	X	X		X	X		X	X	X		X	X		
MOIST	1D-HM	X	X		X	X	X			X		X	X		
MOIST-EXP.	1/2D-HAM	X	X	X	X	X	X	X	X	X	X	X	X	X	X
UMIDUS	1D-HM	X	X		X	X	X					X	X		
WUFI (**)	1/2D-HM	X	X		X	X	X	X	X	X		X	X		

(*) IDA-ICE version with HAMWall; (**) WUFI family: WUFI-Plus, WUFI-2D, WUFI-Pro and WUFI-ORNL/IBP. A free research and education version of WUFI-ORNL/IBP for USA and Canada is available.

List of symbols:

1– Temperature
2 – RH / Humidity ratio / Dew point / Vapour pressure/concentration
3 – Air pressure
4 – Solar radiation
5 – Wind speed
6 – Wind direction
7 – Horizontal rain
8 – Long-wave exchange
9 – Cloud index
10 – Water leakage
A –Temperature
B – RH / Humidity ratio / Dew point / Vapour pressure/concentration
C – Air pressure
D – Interior stack effect (T and RH)

Table 2. Some information of the 14 hygrothermal models available to the public in general.

2. Case Study 1 – Interstitial condensations

2.1 Steady-state *vs.* transient simulations

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 case study 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 (see Ramos *et al*. (2009)). 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 5.0 developed by the Fraunhofer Institute of Building Physics, allows for analysis under transient conditions.

The model used by WUFI 5.0 is based on the standard 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 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 electro-kinetic 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 software Condensa 13788 applies the model defined by the standard 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 rain are neglected.

2.2 Numerical results

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.

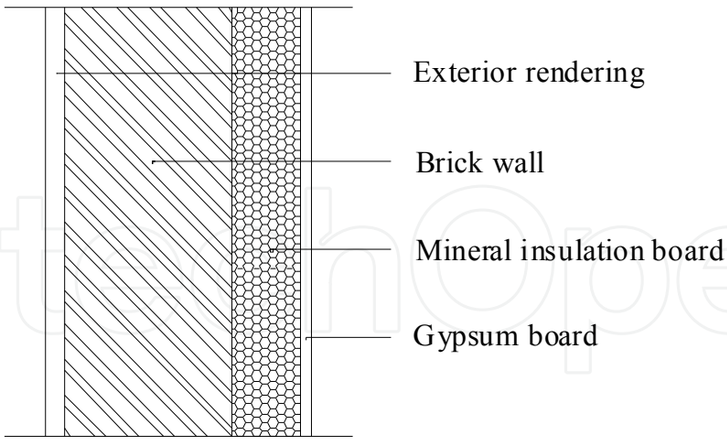

Fig. 1. Building component under study – exterior wall with interior insulation.

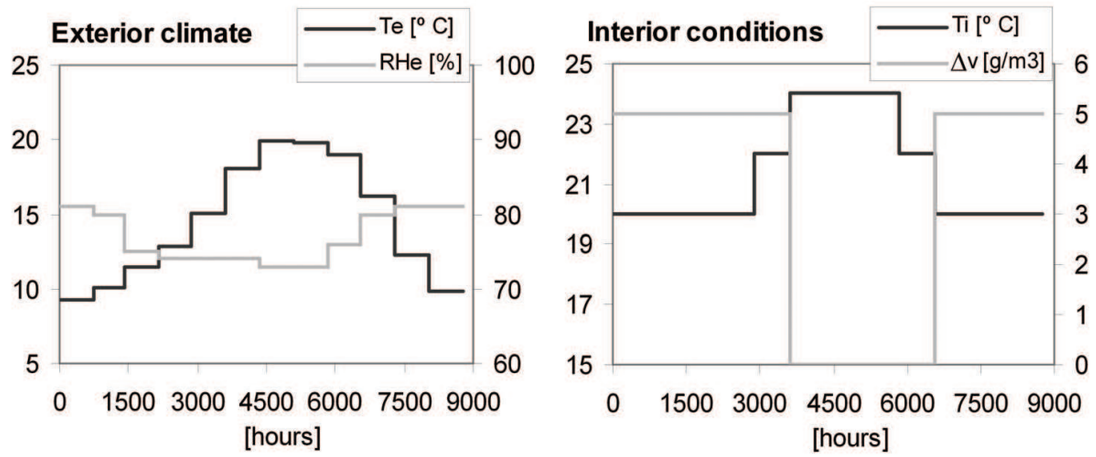

Fig. 2. Boundary condition for simulation.

2.2.1 Simulation with Condensa 13788

Condensa 13788 allows the risk assessment for interstitial condensation according to the standard EN13788 (2002). The material properties (see Table 3) necessary for the simulation with Condensa 13788 are the thermal conductivity (λ) and the water vapour diffusion resistance factor (μ), derived from vapour permeability.

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

Table 3. Material properties required by Condensa 13788.

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

$$g = \frac{\delta_a}{\mu} \cdot \frac{\Delta P}{\Delta x} = \delta_a \frac{\Delta P}{s_{\mathrm{d}}} \tag{1}$$

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,

$$q = \lambda \frac{\Delta T}{d} = \frac{\Delta T}{R} \tag{2}$$

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.

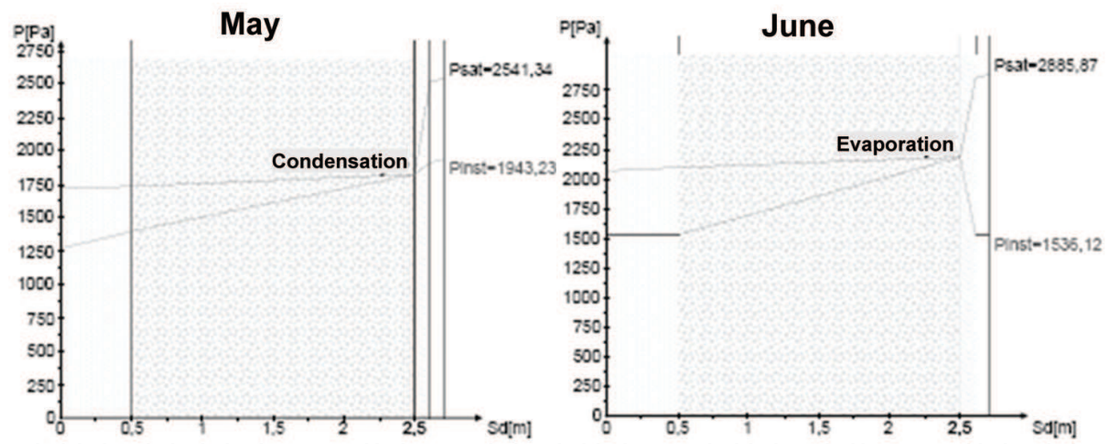

Fig. 3. Condensa 13788 graphical output.

Table 4 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 if 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.

Month	Time [h]	θ_e [°C]	φ_e [%]	P_e [Pa]	θ_i [°C]	Δv [g/m³]	P_i [Pa]	gc_1 [kg/(m²s)]	Ma_1 [kg/m²]
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

Table 4. Condensa 13788 simulation results.

2.2.2 Simulation with WUFI 5.0

The WUFI 5.0 allows for the calculation of the transient hygrothermal behaviour of multi-layer building components exposed to natural climate conditions (see Kuenzel and Kiessl (1996)). This program 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,

$$\frac{\partial w}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \nabla\left(D_\varphi \nabla \varphi + \delta_p \nabla(\varphi\, p_{sat})\right) \tag{3}$$

$$\frac{\partial H}{\partial T}\frac{\partial T}{\partial t} = \nabla\left(\lambda \nabla T\right) + h_v \nabla\left(\delta_p \nabla(\varphi\, p_{sat})\right) \tag{4}$$

where w is water content (kg/m³), φ is the relative humidity (%), t is the time (s), D_φ is the liquid conduction coefficient (kg/ms), δ_p is the vapour permeability (kg/m.s.Pa), p_{sat} is the saturation vapour pressure (Pa), H is the enthalpy (J/m³), T is the temperature (K) 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,

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

where P_n is the normal atmospheric pressure (Pa).
European standard EN 15026:2007 provides minimum criteria for simulation software used to predict one-dimensional transient heat and moisture transfer in multi-layer building components exposed to transient climate conditions on both sides, and WUFI 5.0 complies

with all requirements of this European standard. WUFI program requirements of material properties include: bulk density (kg/m^3), porosity (m^3/m^3), heat capacity (J/kgK), water content (kg/m^3) *vs.* relative humidity, liquid transport coefficient (suction and redistribution) (m^2/s) *vs.* water content (kg/m^3), heat conductivity (W/mK) *vs.* water content (kg/m^3) and diffusion resistance factor *vs.* relative humidity (%).
The application of WUFI 5.0 in the case study provides the variation with time of the moisture content in the building element and in each layer (see Figure 4). It is also possible to know the moisture content profile at a given point in time (see Figure 5).

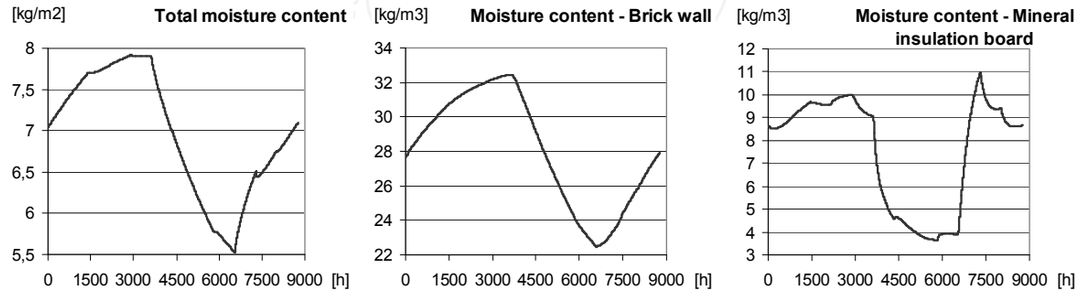

Fig. 4. Component moisture content variation over time in WUFI 5.0 simulation.

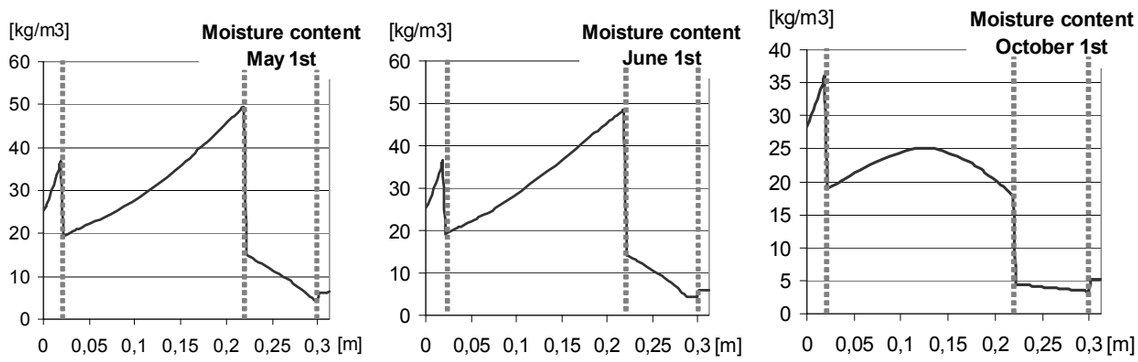

Fig. 5. Component moisture content profiles in WUFI 5.0 simulation.

2.3 Discussion

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

a. The application of Condensa 13788 is less demanding regarding material properties. Admitting steady state condition, moisture retention curves are not necessary. It must 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;
b. Results interpretation, in the case of Condensa 13788 demand less basic building physics knowledge to perform interstitial condensation risk assessment;
c. The results from WUFI 5.0 allow for extensive knowledge on each layer's moisture content development over time. This type of information is important for component

optimization since it supports a detailed risk control strategy. As an example, it's possible to evaluate the increase of thermal conductivity of the mineral wool layer, due to the increase in moisture content during winter;

d. Both programmes indicated that, for the case study, interstitial condensation or the increase in moisture content would not cause severe damage, since the component would regain equilibrium during summer. But the more detailed simulation pointed out the decrease of insulating capacity during winter (see Figure 6). This is due to the moisture content increase in mineral wool which implies an increase of thermal conductivity.

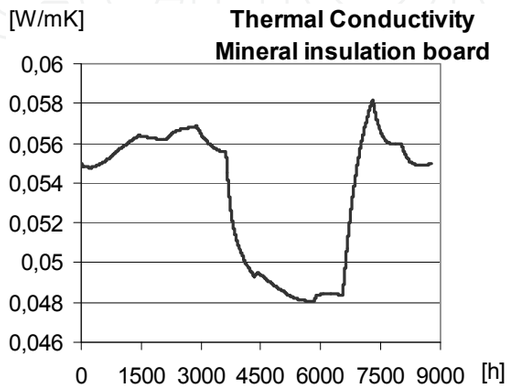

Fig. 6. Thermal conductivity variation over time in WUFI 5.0 simulation.

3. Case Study 2 – External condensations

3.1 Overview of the analysed models

One important characteristic of HAM models is the ability to simulate the radiative balance in the exterior surface. In fact, most models use a simplified method to assess surface temperature on the exterior layer that only considers explicitly the effect of solar radiation. The effect of the long-wave radiation exchange is modelled as a constant parameter, independent of the surface itself, and is included in the heat transfer coefficient value.

Solar radiation, considered as a source of heat that increases the surface temperature during the day, depends on short-wave radiation absorptivity, α_s, and on the solar radiation normal to component surface, I_s (Hagentoft, 2001)

$$q_S = \alpha_S \times I_S \tag{6}$$

The heat flux, q_{cr}, between the surface and the exterior air is given by their temperature differences, T_s and T_a. The heat transfer coefficient, h, consists in 2 parts, one dealing with convection, h_c, and the other with long-wave radiation, h_r.

$$q_{cr} = h \times \left(T_a - T_s\right) \tag{7}$$

$$h = h_c + h_r \tag{8}$$

The radiative heat transfer coefficient, h_r, specifies the long-wave radiation exchange between the building surface and other terrestrial surfaces (sky included), that is governed

by the Stefan-Boltzmann Law (σ is the Stefan-Boltzmann constant). As all surrounding surfaces of the building have similar temperatures, the heat flux, q_r, dependent on the fourth power of the temperature, can be linearized in good approximation. Since normally the temperatures of the terrestrial surfaces are not known, they are assumed to be identical to the air temperature. Furthermore, is also assumed that all objects have similar emissivities, ε, as long as they are non-metallic, which is usually the case in the context of building physics. Three of the four powers of the temperature are lumped together with the radiative heat transfer coefficient and a simple linear relationship analogous to the convective heat transfer is obtained (Hagentoft, 2001).

$$q_r = \varepsilon_t \times \sigma \times T_a^4 - \varepsilon_s \times \sigma \times T_s^4 \approx h_r \times \left(T_a - T_s\right) \tag{9}$$

$$h_r = 4 \times \varepsilon \times \sigma \times T_0^3 \tag{10}$$

where T_0 is an average temperature depending on the surface, the surrounding surfaces and the sky.

Although these temperatures change in time, in most formulations they are assumed as constant. Providing that outside surfaces have similar emissivity, a constant value for the radiative heat transfer coefficient may be adopted. This simplification is quite appropriate for most hygrothermal simulations, however to assess the undercooling phenomenon in walls covered with external thermal insulation composite systems – ETICS more accuracy in the exterior layer is needed. The low thermal capacity of the external rendering and its thermal decoupling emphasises the influence of boundary conditions, mainly temperature and radiation.

It is known that undercooling phenomenon, which occurs mostly during the night, is caused by long wave radiation exchange between the exterior surface and its surroundings. The radiant balance of a building façade is affected by the building's radiation, the sky's radiation and terrestrial surface's radiation (Barreira *et al.*, 2009). A building, being a grey body, emits long wave radiation that can be calculated using the Stefan-Boltzmann Law. On the other hand, the façade absorbs part of the long wave radiation emitted by surrounding surfaces and by the sky. Terrestrial radiation is the sum of long wave radiation emitted by the terrestrial surfaces (ground, other building façades, obstacles, etc.) that also behave as grey bodies and whose temperature is similar to the building's temperature. Therefore, terrestrial surfaces and the building emit long wave radiation at identical intensities.

Atmosphere may behave in two distinct manners. If the sky is cloudy, the atmosphere behaves like a grey body whose temperature is identical to the building's, and emits radiation in a continuous spectrum at intensity similar to that of terrestrial surfaces. If the sky is clear, the atmosphere stops emitting continuously for all wavelengths and the atmosphere's emitted radiation decreases considerably. The radiation emitted by the surface is, therefore, greater than the one that reaches the surface, causing a heat loss.

This negative balance that is not compensated by solar radiation during the night causes the building's surface temperature to decrease, which is maintained until heat transport by convection and by conduction compensate for the loss by radiation. Condensation takes place whenever the surface temperature is lower than the dew point temperature.

For this reason, the influence on the exterior surface temperature of the numerical treatment of the radiative balance will be analyzed in detail in the following paragraphs.

In this case study, three hygrothermal models, WUFI 5.0, hygIRC-1D and HAM-Tools, were used to compare the results of a case study under natural conditions. These simulations used real climatic variables and actual material properties to determine temperature dynamics.

The governing equations of WUFI 5.0 for moisture and energy transfer are given by Eqs. (3) and (4), respectively. The hygIRC-1D governing equations for moisture, heat, air mass and momentum balance are, respectively,

$$\frac{\partial w}{\partial t} + \nabla\left(u\rho_v + K\rho_{\mathrm{w}} g\right) = \nabla\left(D_{\mathrm{w}}\nabla w + \delta_{\mathrm{p}}\nabla p_{sat}\right) + m_s \tag{11}$$

$$c_p \rho \frac{\partial T}{\partial t} + \nabla\left(u\rho_a c_{pa} T\right) = \nabla\left(\lambda \nabla T\right) + L_v\left(\nabla(\delta_p \nabla p_{sat})\right) - L_{ice}\left(w\frac{\partial f_l}{\partial t}\right) + Q_s \tag{12}$$

$$\nabla\left(\rho_a u\right) = 0 \tag{13}$$

$$-\nabla\left(p_a \frac{k_a}{\eta}\nabla P\right) = 0 \text{ with } u = -\frac{k_a}{\eta}\nabla P \tag{14}$$

where u is the air velocity, ρ_v is the water-vapor density, K is the liquid-water permeability, ρ_{w} is the density of water, g is the acceleration due to gravity, D_w is the moisture diffusivity, m_s is the moisture source, c_p is the effective heat capacity, ρ is the dry density of the material, ρ_a is the density of air, c_{pa} is the specific capacity of air, L_v is the latent heat of evaporation/condensation, L_{ice} is the latent heat of freezing/melting, f_l is the fraction of water frozen, Q_s is the heat source, k_a is the air permeability and η is the dynamic viscosity.

Finally, HAM-Tools governing equations for moisture and energy transfer are,

$$\frac{\partial w}{\partial t} = -\frac{\partial}{\partial x}\left(K\frac{\partial s}{\partial x} - \delta_{\mathrm{p}}\frac{\partial p}{\partial x} + g_a u\right) \tag{15}$$

$$\rho c_p \frac{\partial T}{\partial t} = -\frac{\partial}{\partial x}\left(-\lambda\frac{\partial T}{\partial x} + g_a c_{pa} T + g_v L_v\right) \tag{16}$$

where s is the suction pressure, g_a is the air flux density and g_v is the water vapour flux density.

Regarding the treatment of the radiation effect on the exterior surface, all the three models use an explicit balance of the long-wave radiation, defining the surface emission, I_e, and the radiation arriving to it, I_l. They are combined with the shortwave radiation components into a collective heat source at the surface which may have positive or negative value, depending on the overall radiation balance: a positive value leads to heating up the component and a negative value leads to cooling it. With this methodology, the exterior heat transfer coefficient only contains the convective part.

$$q = \alpha_s \times I_s + \varepsilon_{l,surf} \times I_l - I_e \tag{17}$$

In Eq. (17), the two first items give the total amount of radiation (short and long) arriving to the surface, as according to Kirchoff Law the emissivity of a surface, $\varepsilon_{l,surf}$, is equal to its long-wave absorptivity. The last item is the radiation emitted by the building surface.

The total solar radiation, I_s, is described as a function of the direct solar radiation normal to component surface, $I_{s,dir}$, of the diffuse solar radiation, $I_{s,dif}$, affected by the atmospheric field of view, g_{atm}, and of the solar radiation reflected by the ground, $I_{s,ref}$, affected by the field of view of the ground, g_{ter}.

$$I_s = I_{s,dir} + g_{atm} \times I_{s,dif} + g_{ter} \times I_{s,ref} \tag{18}$$

The total long-wave radiation arriving to the surface, I_l, depends on the downward atmospheric radiation, $I_{l,atm}$, affected by the atmospheric field of view, g_{atm}.

$$I_l = g_{atm} \times I_{l,atm} \tag{19}$$

The sky radiation is ruled by the Plank Law, considering the concept of effective sky temperature, which can be defined as the temperature of a blackbody that emits the same amount of radiation as the sky (Martin and Berdahl, 1984). The effective sky temperature depends on several atmospheric conditions, which are rarely available. For that reason, it is assumed that the sky behaves like a grey body, ruled by Stefan-Boltzmann Law, considering the sky emissivity and the air temperature near the ground (Finkenstein and Haupl, 2007).
The downward atmospheric radiation in a specific location may be obtained through measurement, using pyrgeometers, or by empirical models (detailed methods are not commonly used because they require the knowledge of atmospheric conditions). According to Finkenstein and Haupl (2007), those empirical models provide satisfactory results for clear sky but the approaches for cloudy sky still point to very different results. The long-wave radiation emitted by the surface, I_e, depends on the surface emissivity, $\varepsilon_{l,surf}$, and temperature, T_{surf}, as it is ruled by the Stefan-Boltzmann Law.

$$I_e = \varepsilon_{l,surf} \times \sigma \times T_{surf}^4 \tag{20}$$

From the above equations, the direct solar radiation normal to component surface, $I_{s,dir}$, is automatically calculated by each model from the direct solar radiation in an horizontal surface, included in the climatic data, using information about the sun position. The diffuse solar radiation, $I_{s,dif}$ is obtained directly from the climatic data. The solar radiation reflected, $I_{s,ref}$, is calculated using solar radiation data (direct in an horizontal surface and diffuse) and the short wave radiation reflectivity of the ground.
The differences between the three models, regarding the heat exchange by radiation in the exterior surface, are related with the way the long-wave radiation emitted by the sky is obtained and the effect of the ground in the balance.
WUFI 5.0 allows two different approaches to obtain the atmospheric long-wave radiation, $I_{l,atm}$, necessary for the calculation: it may be read directly from the climatic file, if it has this information available, or it may be calculated using the cloud index data. This model also considers the emission and reflection of long-wave radiation by the ground, adding to eq. (19) two extra items: the long-wave radiation emitted by the ground, calculated by the Stefan-Boltzmann Law assuming that the ground has the same temperature as the air and inputting the ground long-wave emissivity, and the atmospheric long-wave radiation reflected by the ground, calculated using the atmospheric long-wave radiation, $I_{l,atm}$, and the long-wave radiation reflectivity of the ground.

HygIRC-1D calculates the atmospheric long-wave radiation, $I_{l,atm}$, necessary for the simulation, using the cloud index information available in the climatic file. The effect of the ground (emission and reflection of long-wave radiation) is not taken into account.
HAM-Tools reads the atmospheric long-wave radiation, $I_{l,atm}$, necessary for the calculation directly from the climatic file. The effect of the ground (emission and reflection of long-wave radiation) is not included in the mathematical treatment.

3.2 Input data

Figure 7 is a schematic of the test façade analysed numerically and Table 5 presents the material properties used in this application. The construction type chosen for comparison of the three hygrothermal models was a wall with external thermal insulation systems (ETICS) exposed to solar radiation.

Wall components	L (cm)	ρ (kg/m^3)	ε (m^3/m^3)	λ (W/mK)	c_p (J/kgK)	μ (-)
Resin finishing coat	0.5	1800	0.12	0.70	840	1000
EPS (Expanded polystyrene)	4	15	0.95	0.04	1500	30
Concrete C12/15	20	2200	0.18	1.6	850	92
Cement plaster - stucco	1.5	1985	0.30	1.20	840	25

Table 5. Material properties of wall components used in the hygrothermal models.

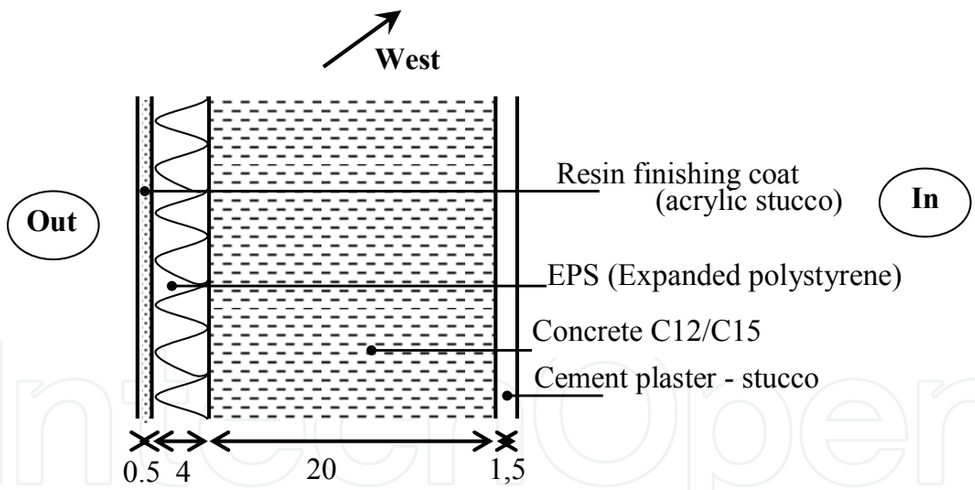

Fig. 7. Wall construction details (dimensions in cm).

The exterior and interior *Sd* value used was zero (no coating) and the interior heat transfer coefficient was constant and equal to 8 W/m²K. The exterior heat transfer coefficient only contained the convective part and was considered independent from the wind (constant value of 17 W/m²K).
All the calculations were done with climate data for Porto city obtained with METEONORM 6.0 (METEOTEST 2008). METEONORM is a software tool that consists of a set of meteorological databases and a series of conversion utilities that prepare and format weather data for use with major hygrothermal modelling software packages. METEONORM calculates hourly values of all parameters using a stochastic model and the

resulting weather data files are produced in a variety of formats. The weather data inputted to the models was temperature (ºC), relative humidity (-), wind direction (°), wind speed (m/s), global solar radiation in a horizontal surface (W/m²) and diffuse solar radiation in a horizontal surface (W/m²). WUFI 5.0 also required information about air pressure (hPa), downward atmospheric radiation in a horizontal surface (W/m²) and cloud index (two climatic file were created, one with downward atmospheric radiation and other with cloud index). HygIRC-1D also included information about the cloud index variation and HAM-Tools also demanded data about the air pressure (hPa) and the downward atmospheric radiation in a horizontal surface (W/m²). In the climatic files rain was inputted equal to zero. The conditions of indoor air were constant, with *RH*=60% and *T*=20º C (comfort values). The short wave radiation absorptivity and the long-wave radiation emissivity considered were 0.4 (stucco-normal bright) and 0.9, respectively, and the initial conditions within the element were *RH*=70% and *T*=15º C. The ground short-wave reflectivity was 0.2 and for WUFI 5.0 the ground long-wave emissivity was 0.9 and the ground long-wave reflectivity was 0.1.

The condensation on surface was assessed by comparing the surface temperature with the dew point temperature of outdoor air. Whenever the surface temperature drops below the dew point temperature condensations occur. The risk of condensation was evaluated by the monthly accumulated value of the positive differences between the dew point temperature of outdoor air and the surface temperature.

3.3 Numerical results and discussion

In this case study simulations were done with three hygrothermal models to analyse the influence of the numerical treatment of the radiative balance in the exterior surface temperature of the wall in Figure 7. All input parameters, including material properties, climatic data, and initial conditions, were made to vary as little as possible between the models in order to ensure a fair comparison.

WUFI 5.0 requires as material properties bulk density (kg/m³), porosity (m³/m³), heat capacity (J/kgK), water content (kg/m³), liquid transport coefficient (suction and redistribution) (m²/s), heat conductivity (W/mK) and diffusion resistance factor.

HygIRC-1D requires similar material properties as WUFI 5.0 but uses different units. The material properties required for simulation are: air permeability (kg/mPas), thermal conductivity (W/mK), dry density (kg/m³), dry heat capacity (J/kgK), sorption curve moisture content (kg/kg), suction pressure (Pa), water vapour permeability (kg/mPas), liquid moisture diffusivity (m²/s) and water content (kg/kg). The liquid moisture diffusivity was assumed the same as the liquid transport coefficient by suction used in WUFI 5.0. The water content was converted from kg/m³ to kg/kg simply by dividing by the density of the material, and to m³/m³ by dividing by the density of the material and multiplying by the density of water (1000 kg/m³). The water vapour permeability and the suction pressure, *s*, were calculated using the water vapour diffusion resistance factor and the Kelvin equation (Galbraith *et al.*, 1997), respectively.

The properties required by HAM-Tools are the density of the dry material (kg/m³), open porosity (-), specific heat capacity of the dry material (J/kgK), thermal conductivity (W/mK), sorption isotherm, moisture capacity, water vapor permeability (kg/msPa) and liquid water conductivity (s).

It was possible to obtain similar temperatures on surface using all the models. The existing differences may be related with the calculations of the solar radiation normal to the surface

that influences mostly the surface temperature during the day, but also after the sunset and at dawn. The differences can also be related with the formulation used to calculate the radiation emitted by the sky (WUFI 5.0_a and HAM-Tools use downward atmospheric radiation in a horizontal surface calculated by meteorological software and WUFI 5.0_b and HygIRC-1D calculate themselves the radiation using cloud index information). Differences in the governing equations and the conversion of the material properties may also have some effects on surface temperatures.

Figure 8 shows the variation in time of the calculated surface temperatures during a winter day (23rd of January) and Figure 9 shows the accumulated degrees of condensation (or the sum of the positive differences between dew point temperature and the surface temperature) for the same day. It is possible to see that surface temperature drops below dew point temperature during the early morning hours for all models, due to the low thermal capacity of the system that allows the dissipation of the heat stored during the day in a few hours after sunset. Condensation occurs during this period of time.

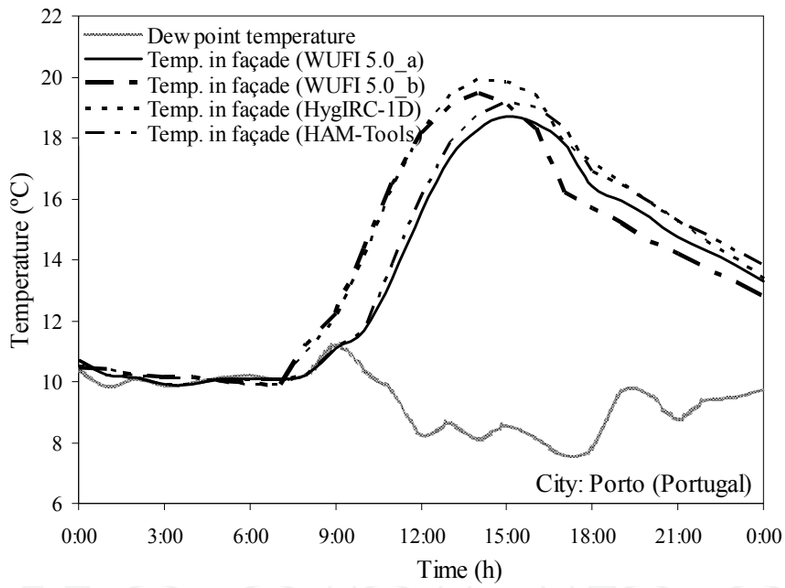

Fig. 8. Surface temperatures obtained by each hygrothermal model for Porto (23-January).

There is however small differences between the models that induce the results presented in Figure 9. Comparing WUFI 5.0_a and WUFI 5.0_b, of which only difference is the long-wave radiation used (in WUFI 5.0_a the radiation used was calculated by meteorological software and in WUFI 5.0_a was calculated by the equations included in the model using cloud index information), it shows that the values inputted for the long-wave radiation influence considerably the surface temperature and consequently the surface condensation. Figure 10 shows that the model used to calculate the atmospheric radiation induces significant differences in the obtained values. This is related with the difficulty in modelling atmospheric radiation with cloudy sky, referred previously. As radiation used in WUFI 5.0_a is higher than the one used in WUFI 5.0_b, surface temperatures are also higher and condensation reduce.

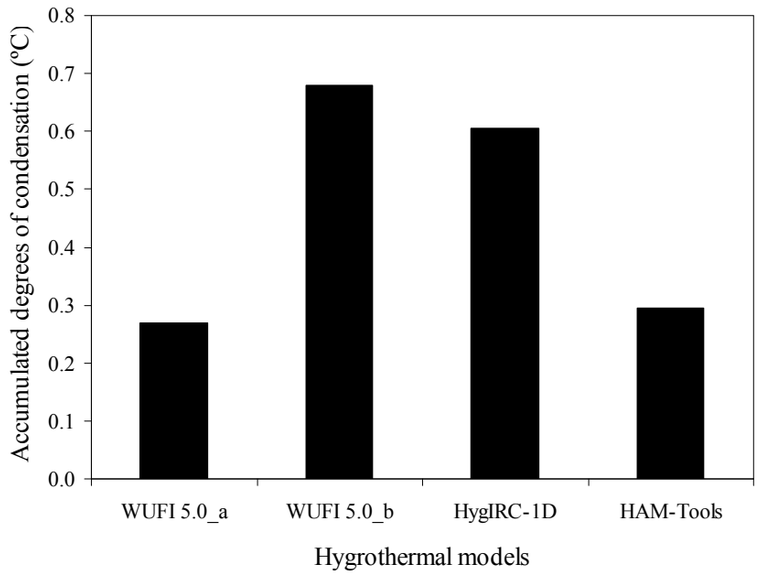

Fig. 9. Sum of positive differences between T_{dp} and T_{surf} for Porto (23-January).

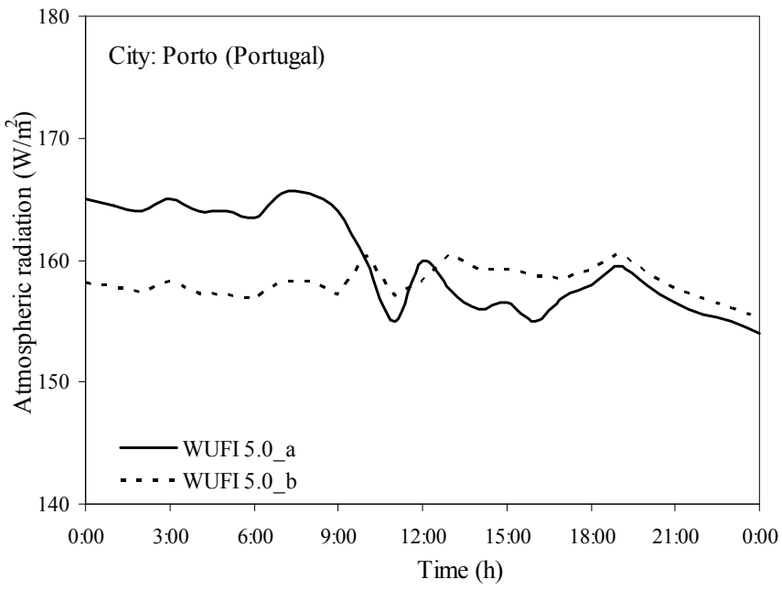

Fig. 10. Atmospheric radiation in a vertical plane in Porto (23-January).

WUFI 5.0_b and HygIRC-1D present very similar variation of the surface temperature, especially during the night. This points to the similarity of the models, not only in term of governing equations but also in terms of boundary conditions. The effect of the ground included in WUFI 5.0_a may not have much influence in the phenomenon or it may compensate some differences existing between the two models. The similar values obtained for the surface temperature are also shown in Figure 9, where the condensation values are also similar. WUFI 5.0_a and HAM-Tools both use the atmospheric radiation calculated by the meteorological software and their results are quite similar. The considerations made previously for WUFI 5.0_b and HygIRC-1D can also be applied to this case.

Figure 11 displays monthly accumulated degrees of condensation. The results show that the most pronounced condensations occur during the late summer, fall and winter months. This is related with the climatic conditions in Porto, a coastal town, namely its high relative humidity and mild temperatures all year-round. However, it should be remarked, once more, that the effect of long-wave radiation is quite clear, as WUFI 5.0_a and HAM-Tools have similar results and WUFI 5.0_b and HygIRC-1D also have similar results, but these two groups don't mach. In fact, the last two (WUFI 5.0_b and HygIRC-1D) have quite higher condensation as radiation is lower.
Figure 11 also shows that there are very few accumulated degrees of condensation in every month, using any program, and this is due to the small differences between the dew point temperature and the surface temperature, which are, on average, around 0.2º C per hour. On the other hand, condensation occurs, on average, only half a hour per day during the year.

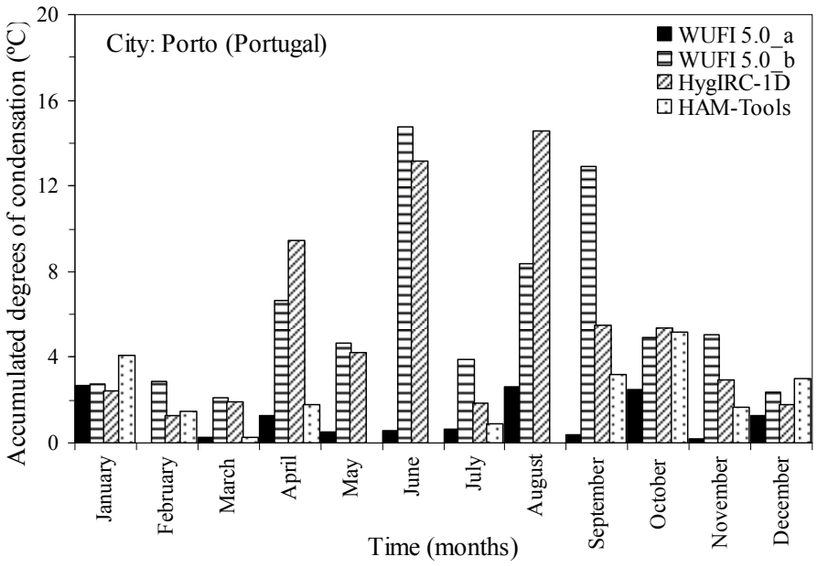

Fig. 11. Sum of positive differences between T_{dp} and T_{surf} for Porto.

4. Conclusion

This book chapter presented a brief review of heat, air, and moisture (HAM) analysis methods commonly used in numerical simulation and methods that allow for their determination. The review has shown that there are numerous hygrothermal models with a range of capabilities and that these models are important tools to better understand the real problems and to provide correct solutions.
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 of 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 if 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.

In the second case study, the numerical results show that these programs are useful tools to simulate the undercooling phenomenon and assessing the exterior condensation on façades, providing that all relevant components of radiation exchange at the exterior surface are included in calculations. The models present similar results except when different inputs of long-wave radiation are used. In fact, it seems to be the key factor for the differences observed in the calculated values. Using cloud index information or measured long-wave radiation, even in the same model, provided the most significant differences.

Using accumulated degrees of condensation, a comparative measure of the risk of condensation on exterior surfaces can be obtained. Since very small differences between surface and dew point temperature contribute to this indicator, the calculations are therefore demanding in terms of required precision.

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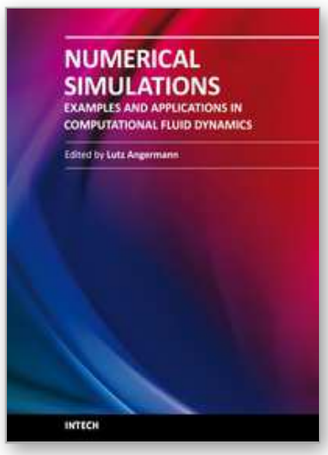

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