Hygrothermal Simulations Comparative Study: Assessment of Different Materials Using WUFI and DELPHIN Software

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Abstract

In building simulations for hydrothermal evaluation there are many uncertainties related to the materials properties, to the initial and boundary conditions and to the calculation methods used for the models. The aim of this paper is to perform a series of hydrothermal simulation with two disseminated solvers: WUFI Pro 4.2 and DELPHIN (Version 5), in order to compare their results, specify the differences between them and identify both their limitation and potentialities. The simulations consider the EN 15026; diverse materials like brick, concrete and plaster, different simulation times (60-days and 2-years) and steady climatic conditions or real climatic data from Munich. Obtained results from the two software programs are very close.

Introduction

For some time, both academy and construction sectors have used computational tools to evaluate the whole building performance and its constructive elements, especially to fulfil the increasing requirements to improve comfort and energy efficiency of new and existing buildings. In this sense, moisture balance and drying capacity of the building directly influence its performance and so, are many available software that couple heat, air and moisture in order to perform hydrothermal evaluations (Chang and Kim, 2015; Kontoleon and Giarma, 2016; Hens, 2015; Mundt-Petersen and Harderup, 2015; Tudiwer et al., 2018). However, when it comes to building simulations there are many uncertainties related to the materials properties, to the initial and boundary conditions and to the calculation methods used for the models (Vertal' et al., 2018; Zhao et al., 2011).

Many software programs have been developed for hygrothermal simulation. A comprehensive review of hygrothermal simulation software tools applied to building physics for simulating the coupled transport processes of Heat, Air and Moisture (HAM) transfer for one- or multi-dimensional cases has been presented by Delgado et al. (2010, 2012).

Until 2012 more than 57 hydrothermal software programs existed, 14 of which were freely available (Delgado et al., 2010; 2012.). Table 1 shows a number of important HAM simulation programs (Delgado et al., 2010). As examples, 1D-HAM is a commercial program for one-dimensional modelling of multi-layered porous materials considering

heat, air, and moisture transport. Conduction, convection and latent heat effects can be considered for heat transfer. Moisture transfer can occur through diffusion and convection in vapour phase but liquid water transport is not modelled. Considering surface absorption of solar radiation is also possible (Hagentoft and Blomberg, 2000). Another commercial software is hygIRC-JD suitable for simulation of heat, air and moisture transport in exterior common walls. A feature of this program can show how much the effectiveness of retrofitting of a wall is. MOIST is a free software for modelling heat and moisture (by diffusion and capillary flow) movement in building envelopes. It calculates the surface relative humidity at the wall layers, studying the effect of moisture on heat transfer and evaluating the winter moisture content in exterior layers. The disadvantages of the program are that it is one-dimensional, it does not consider wetting the exterior by rain, it does not model heat and moisture transport by air movement, and it assumes that the construction is air tight, and it includes only the weather data of USA and Canada (Delgado et al., 2010).

DELPHIN (2018) is a commercial software program. The DELPHIN program can be used for simulating one-, two- and asymmetrical three-dimensional transport of heat, air, moisture, pollutant, and salt transport in porous building materials, assemblies of such materials, and building envelopes in general (Grunewald, 1997; Nicolai et al., 2008). It can simulate transient mass and energy transport processes for arbitrary standard and natural climatic boundary conditions including temperature, relative humidity, wind-driven rain, wind speed, wind direction, and short- and long-wave radiation. An important feature of this software is that it can study variations in different materials and climates and also many parameters such as temperature, moisture content, diffusive and advective flux of water, and air pressure can be obtained as functions of position and time (Nicolai et al., 2008).

The WUFI (Wärme- Und Feuchtetransport Instationär (Heat and Moisture Transiency)) program is commercial and can be used for simulating one- and two-dimensional transient hydrothermal behaviour of multilayer building components exposed to standard or natural climatic conditions. The software has been validated many times with field and laboratory results (Künzel, 1995). The program includes conductive heat transfer, enthalpy flow, short-wave solar radiation and long-wave radiative

cooling. Water movement is covered by capillary and surface diffusion.

Although there are good established theories and complete computational solvers for hydrothermal simulations, the numerical models are still simplifications of the physical events that occur in reality. In addition, the programs always give outputs, even if the inputs are not suitable for the case that the software pursuit to represent. As a result, numerical model calibration and the reliability of calculations are subjects that demand discussion.

One actual gap are studies that associate software such as WUFI (2018) and DELPHIN (2018), showing how each variable directly influence the outcomes and how they present results close or not when compared with real evaluations. A number of studies have compared the two WUFI and DELPHIN software programs. Delgado et al. (2012) used two hydrothermal models for verification purposes. DELPHIN was used to verify the WUFI model. The results for the temperature were good but there was some disagreement for humidity. Carbonez et al. (2015) used the two programs to simulate a water leak in a wood-frame wall. The results were validated by experimental tests and it was concluded that DELPHIN gives more realistic results for moisture.

In literature, there are very few studies dedicated to the comparison of results obtained from WUFI and DELPHIN software for prediction of the hygrothermal performance of materials. This research contributes to the state of art of hygrothermal computational simulation, by comparing results from WUFI and DELPHIN programs for three different materials.

Table 1: A number of hygrothermal programs (Delgado et al., 2010).

Software	Type
1D-HAM	1D heat-air-moisture
BSim2000	1D heat-moisture
DELPHIN 5	1/2D heat-air-moisture-pollutant-salt
HAM	1D heat-air-moisture
HAMLab	1/2/3D heat-air-moisture
hygIRC-1D	1D heat-air-moisture
hygIRC-2D	2D heat-air-moisture
LATENITE	2D heat-moisture
MATCH	1D heat-air-moisture
MOISTURE-EXPERT	1/2D heat-air-moisture
WUFI-2D	2D heat-moisture
WUFI-ORNL	1D heat-moisture
WUFI-Plus	1D heat-moisture
WUFI-Pro	1D heat-moisture

Comparison with EN 15026

In the first step, the accuracy of the two software programs were compared in the limits proposed by EN 15026 (2007). The obtained results for the temperature shown in Figure 1 are well within the EN 15026 limits. In the first 30 days, the temperature values calculated by

DELPHIN are slightly higher than WUFI. After one year, the two programs have nearly the same results.

Figure 1: Results from EN 15026 simulations (temperature data).

Experimental test

In this sense, this research seeks to compare the impedance results of a long-term experimental test with the moisture content outputs from two different hygrothermal software. Relative humidity and temperature data are used to validate the numerical model and the work aims to show a correlation between impedance measurements and simulated moisture content values.

One type of sandstone cut into uniform cubes, each having a side length of 40 mm (Figure 2), and a wide properties range (Table 2) were placed inside the chamber. The water adsorption was varied exclusively by changes in the humidity, using saturated aqueous salt solutions.

Figure 2: Analysed sandstone.

Table 2: Properties of the analysed stone.

Stone	Properties		
	Dry thermal conductivity	Dry bulk density	Porosity
	λ W/mK	ρ kg/m ³	Φ m ³ /m ³
M	1,71	2157,73	0,185

Stone	Properties		
	Water vapour resistance	Specific heat capacity	Water uptake coefficient
	μ -	Cp J/kgK	Aw Kg/(m ² √s)
M	148,41	814,544	0,00904087

1D WUFI and DELPHIN numerical simulations

The 1D numerical models created using the DELPHIN 5.0 (B.C. Bauklimatik Dresden 2017) and WUFI 4.0 (I.B.P. Fraunhofer 2015) were developed in order to verify the experimental test findings.

Exterior boundary condition used as input, were the hourly data of temperature and relative humidity measured inside the chamber. As for the interior boundary condition, the values were assumed as constant, and set to 21°C and 55% RH. The 1D numerical models had the same dimensions as the sample stones used in the experimental test (40 mm) and considered the properties listed in Table 2. The computational grid size was composed by elements that varied from 2 mm (at the boundaries) to 7 mm thick (in the middle).

The results of both WUFI and DELPHIN software for temperature (°C) and moisture content (kg) were compared with experimental results for the position of installed sensors (Figures 3 to 6). Comparing the obtained results from the two software shows that the total water content curves have similar behaviour despite the difference in values; DELPHIN gives higher values than WUFI. Based on the measured impedance (which is inversely proportional to the moisture content) in the laboratory, this behaviour is acceptable (Figure 6). In addition, obtained results for the temperature by the two computer solvers DELPHIN and WUFI and the values measured results in the laboratory show high coefficients of determination (R^2) values, more than 0.99. Altogether, good agreement is observed between numerical and experimental results and it can be concluded that validation is achieved.

Figure 3: Result of comparing temperature between DELPHIN software and measured results in the laboratory.

Figure 4: Result of comparing temperature between WUFI software and measured results in the laboratory.

Figure 5: Result of comparing temperature between WUFI and DELPHIN software.

Figure 6: Result of comparing impedance(measured) and water content between WUFI and DELPHIN software .

Case description

The method of the validation of the the DELPHIN and WUFI software was described in the previous section. In this section, further numerical simulations are carried out in order to compare the results from the two software. For this reason, different materials such as brick, concrete and plaster (Table 3), different simulation times (60-days and 2-years) and steady climatic conditions or real climatic data from

Munich have been used.

Table 3: Properties of analysed materials.

Material	Properties						
	Thermal Conductivity	Density	Porosity	Water vapour resistance	Adsorption at 80% RH	Specific heat capacity	Water uptake coefficient
	λ (W/mK)	ρ (kg/m ³)	Φ (m ³ /m ³)	μ -	W80 (m ³ /m ³)	Cp (J/kgK)	Aw (kg/(m ² √s))
Brick	0.8112	1787.9	0.325	28.287	0.0005	799.734	0.311
Light concret	0.6035	1503	0.432	81.29	0.0882	1074.22	0.0319
Plaster	0.55	1270	0.5	12	0.0596	850	0.0093

Table 4: Input data for parametric study.

Material	Thickn ess (m)	Time	Outside climate	Surfaces	Indoor climate	Intital conditions
Brick	0.28	*60 Days (01.10.2018 to 01.12.2018)	a. Moisture +temperatur e b. Munich	Outer wall, Partition wall	Constant, Sinusoid, EN 15026, EN 13788 (Humidity class: 1)	01) *TB/ IK =Component 80%/ Water content=4.5 kg/m ³ * TB/ IK = layer / Water content=100 kg/m ³
Light concrete	0.28					
Plaster	0.28	*2 Years 01.01.2018 to 01.01.2020)		- Entertaining radiation absorption number: 0.4	Constant:

- Long-wave radiation emission number: 0.9	21 °C, Moisture =50% Sinusoid: 1. Temperature: Average: 21 °C, Amplitude: 1°C Day of maximum :03.06.2018 2. Relative humidity: Average: 50% Amplitude:10% Day of the maximum:16.08.2018	02) *TB/ IK = component 80%/ Temperature in Component :20 °C Water content =53 kg/m ³ * TB/ IK =layer/ Water content =175kg/m ³ 03) *TB/ IK =Component 80%/ Temperature in Component =20 °C Water content =30kg/m ³ * TB/ IK = layer/ Water content =250 kg/m ³
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Table 5: Two methods used for calculating hydrothermal behaviour of materials.

Method No.	Outside climate	Surfaces	Inside climate	Initial moisture
1	Humidity and temperature	Partition wall	Constant	Constant over the component
2	Humidity and temperature	Partition wall	Sinusoid	Constant over the component

Table 6: Coefficient of determination (R^2) values.

Method No.		External temperature	Centre temperature	Internal temperature	External humidity	Internal humidity	Total water	Centre water
1	Brick	0.9996	0.9977	0.999	0.9947	0.9751	0.9815	0.9878
	Light concrete	0.9994	0.9905	0.999	0.9715	0.919	0.8674	0.8483
	Plaster	0.9979	0.9628	0.9951	0.9484	0.8436	0.9249	0.8746
2	Brick	0.9994	0.9914	0.9983	0.9936	0.9349	0.981	0.9199
	Light concrete	0.9994	0.9851	0.9986	0.9719	0.8939	0.7802	0.9344

For parametric study, 194 simulations with different conditions as shown in Table 4, have been performed. The thickness of each material was 28 cm. Humidity and temperature conditions of Munich were used for outside climate. For inside climate, two different climate conditions were considered. For the first inside climate condition, called here method 1, the conditions were constant, i.e. temperature equal to 21 °C and moisture equal to 50%. For the second inside climate conditions, called here method 2, the inside climate was considered sinusoid according to EN 15026 (Tables 5 and 6). Initial conditions are shown in Table 4.

Results

Results obtained from simulation for method 1 and material 1 (Brick) have been shown in Figures 7 to 12 and Table 6. Figure 7 indicates that the variation of internal

temperature versus time is almost identical for the both software with $R^2=0.9985$. The variation of centre and external temperatures are also the same with $R^2=0.9992$ and 0.9996, respectively (Figures 8 and 9). Figure 9 shows that the external temperature has an irregular variation between 0°C and 10°C. According to Figure 8, the variation of centre temperature is still irregular but the temperature ranges from 3°C to 13°C. Figure 7 indicates that the changes of internal temperature is between 13°C and 17°C.

According to Figures 10 and 11 the internal and external humidities estimated by the both software are very close with $R^2=0.99$. External humidity has a high variation between 32% and 82%, whereas the variation of internal humidity is more regular and between 52% and 80%.

Figure 12 shows that total water calculated by DELPHIN is more than WUFI with $R^2=0.94$. DELPHIN indicates

that water content reduces from 1.25 kg/m² to 1.15 kg/m², whereas WUFI anticipated the reduction of water content from 1.25 kg/m² to 0.57 kg/m², which is about half of DELPHIN. The same trend is observed in the results of experimental tests shown in Figure 6.

Carbonez et al. (2015) encountered a similar discrepancy between the results of DELPHIN and WUFI, and attributed it to the liquid transport formulations in two software programs. In the formulation for DELPHIN, Equation (1), an additional gravitational component ($\rho_l g$) is included compared to the formulation for WUFI, Equation (2), which causes the water content at the end of wetting period in DELPHIN be higher than WUFI.

$$j_l = -K_l \left[\frac{\partial p_l}{\partial x} + \rho_l g \right] \quad (1)$$

$$j_l = -D_l(w) \frac{\partial w}{\partial x} \quad (2)$$

with j_l the liquid moisture flux, K_l the liquid conductivity, p_l liquid pressure, ρ_l density of liquid, g the gravity constant, D_l the liquid diffusivity, and w the moisture content.

Figure 7: Internal temperature.

Figure 8: Centre temperature.

Figure 9: External temperature.

Figure 10: Internal relative humidity.

Figure 12: Total water content.

Figure 11: External relative humidity.

The coefficient of determination (R^2) values for brick (material 1), light concrete (material 2) and plaster (material 3) for temperature, humidity and water calculated by two methods are presented in Table 6. Of these two methods, the method 1 provides slightly better results than the method 2, because it has larger values of R^2 .

Conclusion

At first, software verifications were performed with a laboratory test, and then a few number of analyses were performed on three types of materials to compare the two software DELPHIN and WUFI.

By simulating three different materials with the DELPHIN and WUFI software programs, the results of external, centre and internal temperatures, external and internal humidity, and total water content were compared. Obtained results from the two software programs are very close, except for total water content during the wetting period. Two methods were used for comparison. The results of the constant inside climate method were better than the sinusoid inside climate method.

For future work, experimental tests will be performed for the three types of materials simulated in this paper in order to validate and compare the results obtained from the two software. In addition, the study will be focused on hygrothermal performance of traditional materials such as adobe and mud-straw and the two software will be calibrated for traditional materials by the use of results obtained from experimental tests performed on traditional materials.

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