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Review Article

HAM and mould growth analysis of a wooden wall

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Abstract

The aim of engineers is to design structures, while minimising their energy dependence and create a suitable environment for living. Some of the most important factors for maintaining the indoor environment are temperature and humidity. Unsuitable combinations of heat and moisture (HAM) could indicate a danger of mould growing. The mould's existence influences the reliability and lifespan of a structure. Some materials, for example wood, are very sensitive to mould growth. To analyse a structure for mould growth risk it is necessary to know the values of temperature and relative humidity on the surfaces and inside of structures. There are two possibilities to acquire these quantities; taking measurements at a construction site or in a laboratory, or applying numerical solutions using an accessible programme. One such programme is Wufi, which has been developed especially for HAM analysis. An advantage of measuring at the construction site is the reality, which is not affected by numerical errors. On the other hand, numerical analysis usually needs lower costs and does not demand so much time to simulate long term periods. From the point of view of accuracy, it is suitable to verify the numerical solution with measurements. The aim of this paper is threefold. First, to analyse the risk of mould growth. Second, it presents a verification of numerically calculated data using Wufi 2D against actual measurement data acquired from a real structure, which is presented by a low-energy house located in Oulu/Finland. Third, to prove that the form of low-energy building structures do not increase mould growth risk. After carrying out the verification, the received outcomes are utilised for mould growth analysis. For an expression of reality in the numerical solution, a transient simulation was needed. The received outcomes were then used for mould growth analyses. There is a possibility to predict real mould growth risk inside the structure and on its surfaces, corresponding to the critical relation between temperature and relative humidity, which separates favourable and unfavourable areas for mould growth.

Keywords: Measuring; Computing; Verification; Mould growth risk

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Contents

1. Introduction

The work presented in this paper is included in the Increasing Energy Efficiency in Buildings (IEEB) project, which is based on the creation of a Nordic network among academia, research, industry and society for developing new solutions and promoting energy efficiency in buildings. The project includes measurements of many different houses in northern Finland to obtain real-life information. This paper deals with measurements in one of the houses obtained. It is a low-energy single-family house located in Oulu/Finland.

There are two main aims of researchers whose work is based on building physic properties of buildings. The first is to create a suitable, comfortable and healthy environment for living inside a house. The second is to build structures with low demands on energy consumption. These factors are closely connected. The low energy consumption is usually achieved by using thick layers of insulation. On the other hand, this brings more air-tight structures, which can lead to an uncomfortable environment for indoor living and also it could assemble substantial quantities of moisture. The after-effect of moisture assembling together with a certain temperature leads to mould growth. Mould is a result of biological processes where microscopic organisms assemble. Mould presence shows an unhealthy environment for living, especially these days, where the amount of people with different allergies increases. Generally, there are three factors needed for the mould to start growing. They are temperature, moisture and exposure time. Despite difficulties with mathematical expressions of biological processes, there has been published a work which describes a mould growing on wooden surfaces (Viitanen and Ojanen, 2007) by a mathematical model. One way to obtain temperature and relative humidity data in a structure is to measure them by installing certain sensors. Although this way is generally considered the most accurate one, errors might appear. This work deals with the errors by using a computing programme, where the real situation was simulated. By a combination of measured and calculated data, all needed temperature and relative humidity data are obtained. The aim of this paper is to analyse the data in the low-energy house (Oulu/Finland) obtained from the point of view of mould growth risk.

2. Analysed house

The house which is subjected to the present analysis is located in Oulu/Finland. It is a one-family timber frame house (Fig. 1), which has been occupied since the end of 2009 and the final building approval was made in summer 2010. During this time the final facial operation, such as cladding panels installation in the garage, painting of exposed wooden elements, etc. had been complete. Regarding to its annual delivered energy which is 49.37 kWh/(m^2a), it complies with conditions for low-energy houses M-50, according to regulation RIL 249-2009 developed by the Finnish Association of Civil Engineers [RIL 249-2009 “Low-energy building in residential building”]. Also calculations and energy research performed by the LaMit (Finnish Energy Services) certificate show that the design solution corresponds to the low-energy building (Thullner, 2010). The total area of the house is 228.5 m^2, heated floor area is 165 m^2 and air volume is 613 m^3. The air tightness of the house has been subjected to Blower Door measurements at a pressure difference of 50 Pa between indoors and outdoors. The air change rate is $n_{50} = 1\ h^{-1}$. Functionality of the ventilation system is 0.085 m^3/s.

3. Measurements

The main point of the research is to monitor a situation of the real temperature and relative humidity values on surfaces of the structure and inside the external walls too. The house presented in this paper is monitored by 37 sensors, which scan temperature and relative humidity values. Twenty are monitoring the situation underneath the house, 12 the external walls and 5 are scanning temperature and relative humidity in the sauna. They were installed in the house while it was under construction, so no part of the structure was damaged due to sensor installation. The sensors for measuring temperature are 1-Wire Parasite-Power Digital Thermometer – DS18S20 with an accuracy

Fig. 1. Analysed house.

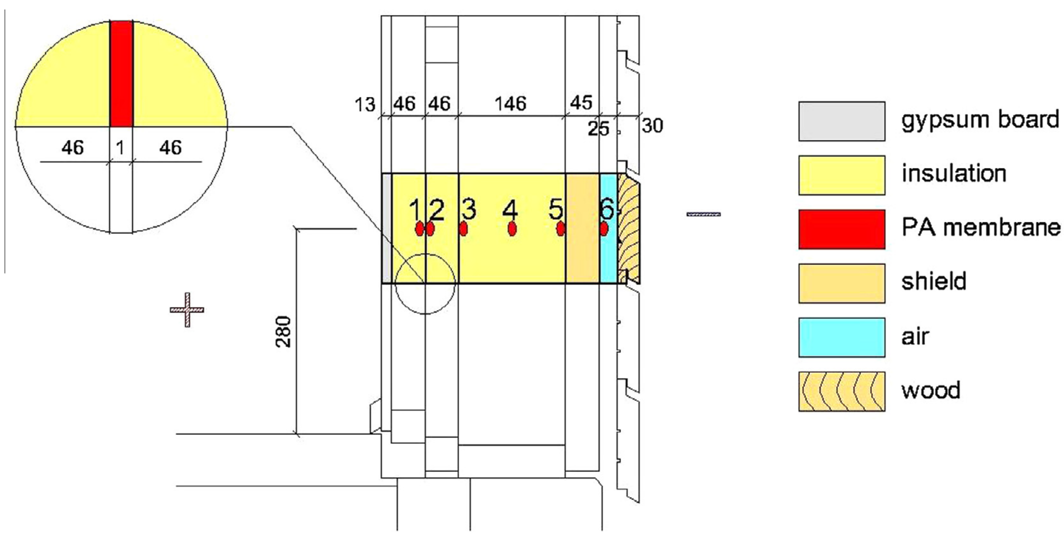

Fig. 2. Sensors location.

upto ±0.5 °C and possibility to operate in temperature ranges −55 to +125 °C. Relative humidity is measured by Honywell S&C – HIH-4021 with a range of 0–100% and accuracy of 3.5% (the numbers are specified by manufacturer). The RH sensors work under 1-Wire Smart Battery Monitor – DS2438, which is connected to the central microprocessor, where we are able to read both temperature and RH values.

This analysis is focused on the situation on the northern side of the house at the bottom of the wall. The monitoring wall is between outdoor conditions and a walk-in closet. With reference to sufficiency of measured data, we installed 6 sensors monitoring the bottom and 6 measuring the upper part of the wall. They are located between certain material layers of the wall in the same horizontal line, which is 280 mm above the floor (except point 4, which is in the middle of the mineral wool layer all the others exactly are in the middle of two different material layers of the wall). Their location is pictured in Fig. 2. Horizontally, they are located in the middle of two studs. By doing this, the influence of vertical wooden studs is minimised.

4. Computing methods

The errors in the measuring obtained lead us to use alternative methods to reach complete information of temperature and humidity in monitored points, which are needed for the next analysis. The Wufi 2D computing programme was chosen. It is a powerful tool designed for the HAM (heat and moisture) analysis of building envelope constructions. It allows us to make two-dimensional models only. The presented analysis enables a one-dimensional calculation. If boundaries, which simulate continuation of the wall vertically are defined as adiabatic, the 1D problem is solved. The adiabatic boundaries do not allow any quantity flow along the y direction, so the 1D problem was solved with the 2D geometry. The model is pictured in Fig. 3 below.

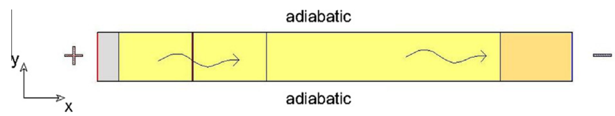

Fig. 3. Boundary conditions of the model.

5. Verification

The measured data obtained from the house contained errors, which are a result of randomly missing or out of range data. This leads us to verify the obtained data with some other available tool. The verification was executed by computing a simulation, where Wufi 2D was used. The aim of the verification was to simulate the real conditions which are to be found in the structure. Material properties used in the model are displayed in Table 1 as follows.

Boundary conditions of the model correspond to outdoor and indoor data in measurements obtained. The outdoor data from point 6 were taken, which means the model does not involve an air gap between shield and wooden cladding. The errors in point 6 and indoor data were replaced by assumed data. The outdoor boundary conditions follow a trend of the temperature and relative humidity values obtained from the weather station at the Oulu University of Applied Sciences. The real time period for simulation was defined as 5.3.2010 (16:00)–30.10.2011 (16:00). The time step is equal to 1 h. The whole amount of time steps is 14,497, which corresponds to 604 days. The Wufi 2D programme does not allow us to start a simulation from the steady state calculation results as the initial point, so the beginning of the simulation does not fit to the real measured data in the points located inside the wall structure. The simulated data are comparable to the real data after approximately 10 days from the beginning of the calculation. The aim of the verification was to simulate the real behaviour of HAM transfer in the wall so that we were able to continue with analysis using completed data in the all monitored points in the structure. The next aim was to present another option to simulate a real situation of HAM transfer. In the next graphs (Fig. 4) are pictured measured data with comparison of outcomes obtained in the simulation.

The verification showed comparable trend from the measured and calculation data obtained. The differences can be influenced by accuracy of the sensors, and also certain simplifications which follow the simulation performed by computing programme. Differences between measured and computed values in all the monitored points obtained are displayed in Table 2, represented by square deviation according to expressions (1) and (2):

$$E_T^2 = \frac{1}{n}\sum_{i=1}^{n}(T_{i,\text{measured}} - T_{i,\text{computed}})^2 \quad (1)$$

for temperature and

$$E_{RH}^2 = \frac{1}{n}\sum_{i=1}^{n}(RH_{i,\text{measured}} - RH_{i,\text{computed}})^2 \quad (2)$$

for relative humidity, where $i = (1,2,3,\ldots,n)$ is number of time steps.

In the Table 2, the incorrect obtained data during measuring are not taken into consideration.

In the next step of the analysis the computed data are only used.

6. Mould growth analysis

A certain combination of temperature and humidity leads to the mould growing. The relation is expressed by Viitanen and Ojanen (2007)with a mathematical expression of critical relative humidity RH_{crit}, which is a function of temperature (3). It is a polynomial function, which describes the boundary for existence of moulds. The mathematical model for the mould growth risk definition is based on long-term lab tests performed by the VTT (Technical Research Centre of Finland) and the Tampere University of Technology (Ojanen et al., 2011) and (Viitanen et al., 2010).

$$RH_{\text{crit}} = \{-0.00267T^3 + 0.161T^2 - 3.13T + 100.0 \text{ when } T \leq 20; 80\% \text{when } T > 20\} \quad (3)$$

where T is a temperature. Graphical expression of favourable and unfavourable area for mould growth depending on temperature and relative humidity is picture in Fig. 5.

The next essential part of mould growth analysis is exposure time. If a structure is subjugated to favourable conditions for mould growth for long periods, the risk of mould existence increases. Otherwise, the mould growth risk decreases. The mould growth risk is determined by seven levels of mould growth, where 0 is for no growth, 1 for small amounts of mould on surface (microscopic), 2 for <10% coverage of mould on surface (microscopic), 3 for 10–30% coverage of mould on surface (visual), 4 for

Table 1
Material properties used in the model.

	Density (kg/m^3)	Porosity (m^3/m^3)	Heat capacity (J/kg K)	Thermal conductivity (W/m K)	Water vapour diffusion resistance factor (−)
Gypsum board	900	0.500	1000	0.250	8.3
Insulation	30	0.950	1030	0.033	1.3
PA membrane	65	0.001	2300	2.900	4380.0
Shield	28	0.600	1030	0.031	1.5

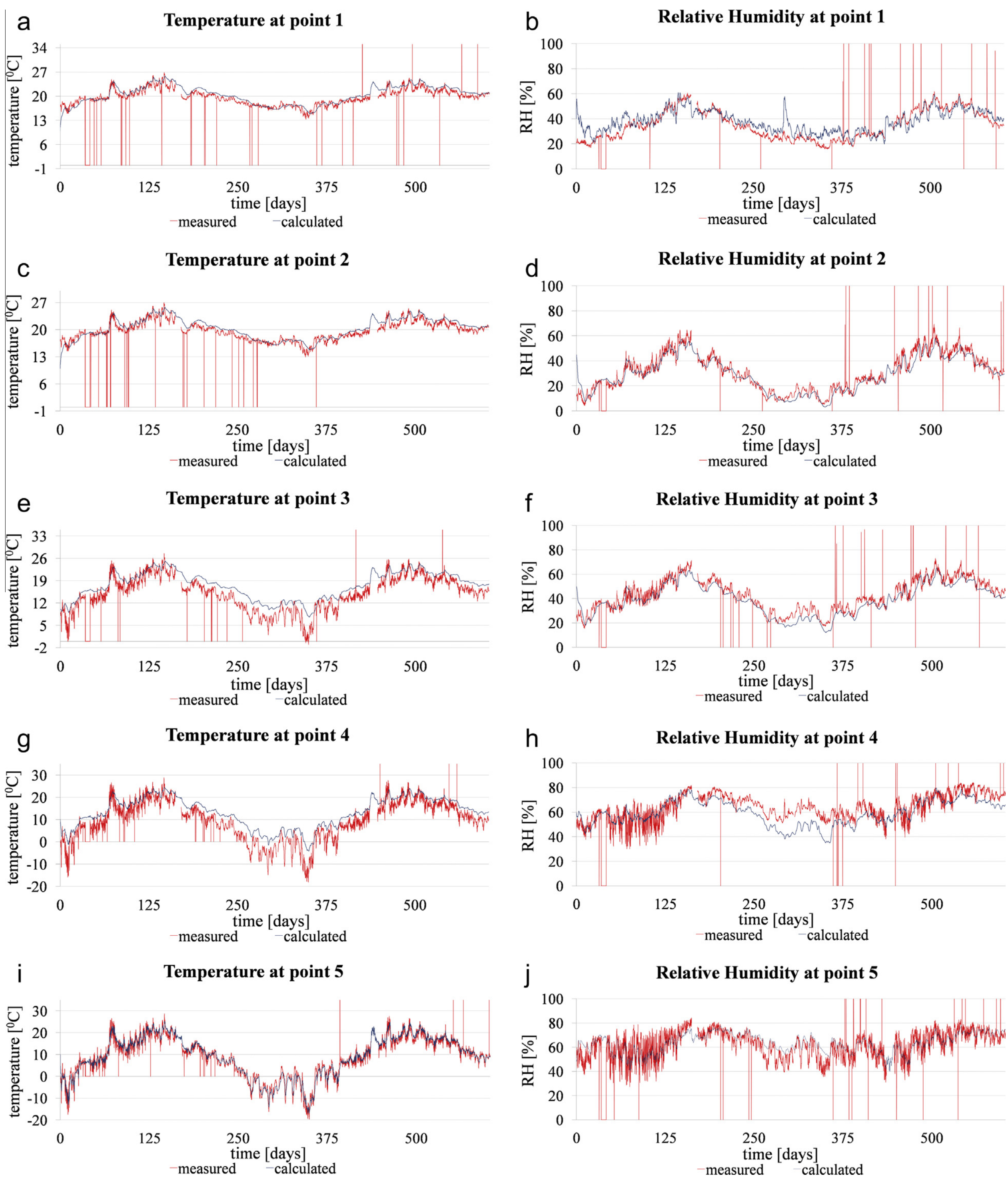

Fig. 4. Verification of calculated data in points 1–5.

30–70% coverage of mould on surface (visual), 5 for >70% coverage of mould on surface (visual) and 7 for heavy and tight growth with 100% coverage. The intensity is expressed by the equation:

$$\frac{dM}{dt} = \frac{1}{168\exp(-0.68\,lnT - 13.9\,lnRH + 0.14W - 0.33\,SQ + 66.02)} k_1 k_2 \quad (4)$$

where W is timber species (0 for pine, 1 for spruce), SQ is surface quality (0 for sawn surface, 1 for kiln dried quality), t is time and k_1, k_2 are coefficients for the growth. In this work constant coefficients for all materials are used. They were chosen to be on the safest side of the solution. So, $k_1 = 1$, $k_2 = 1$, $SQ = 0$ and $W = 0$. The decreasing of mould growth is described as follows:

Table 2
Differences in verification of measured data.

	E_T (°C)	E_{RH} (%)
Point **1**	1.0	2.5
Point **2**	1.0	2.3
Point **3**	2.3	2.4
Point **4**	2.7	2.6
Point **5**	1.4	2.6

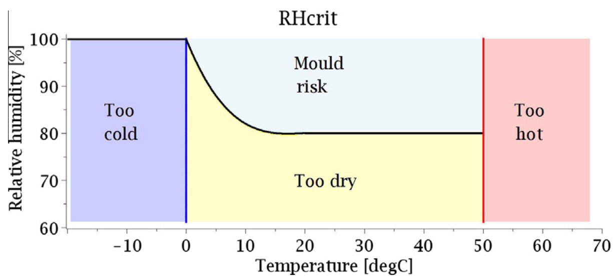

Fig. 5. Favourable and unfavourable area for mould growth.

$$\frac{dM}{dt} = \begin{cases} -0.00133, & \text{when} \quad t - t_1 \leq 6\,\text{h} \\ 0, & \text{when} \quad 6\,\text{h} \leq t - t_1 \leq 24\,\text{h} \\ -0.00067, & \text{when} \quad t - t_1 > 24\,\text{h} \end{cases} \tag{5}$$

For a longer period the mould index decreasing is in the linear progress.

The mould growth risk analysis was performed in each time step of the solution for a period of 1 year, from 31.7.2010 (11:00) to 31.7.2011 (11:00), where 1 time step is equal to 1 h.

7. Results and discussion

The completed data in the measuring and the calculation obtained were used to analyse a mould growth risk in the defined points of the external wall. Three factors are included in the analysis. They are temperature, relative humidity and exposure time. In addition to the mould index values corresponding to Eq. (4), data in each time step of the solution are analysed to obtain a general view of the mould growth risk. The results in the analysis obtained are summarised in Table 3.

The mutual relation between temperature and relative humidity values in each time step is pictured in Fig. 6 with data obtained in point 5.

The pictured data show no risk of mould growth in any time step of the analysis, because they are located under the critic relative humidity curve. Closer to the exterior side of the wall the time step points are nearer to the RH_{crit}, but they do not exceed the critic value. Because of the defined constants in the Eq. (4), we assume the reality would be

Table 3
Mould risk analysis – favourable and unfavourable areas for mould growth and mould index.

	Time steps in unfavourable area (%) no risk	Time steps in favourable area (%) no risk	Time steps in favourable area (%) with risk	Mould index without considering of decrease	Mould index with considering of decrease
Indoor	100.000	0.000	0.000	0.000	0.000
Point **1**	100.000	0.000	0.000	0.000	0.000
Point **2**	100.000	0.000	0.000	0.000	0.000
Point **3**	100.000	0.000	0.000	0.000	0.000
Point **4**	100.000	0.000	0.000	0.000	0.000
Point **5**	100.000	0.000	0.000	0.000	0.000
Outdoor	85.297	7.404	7.299	0.621	0.000

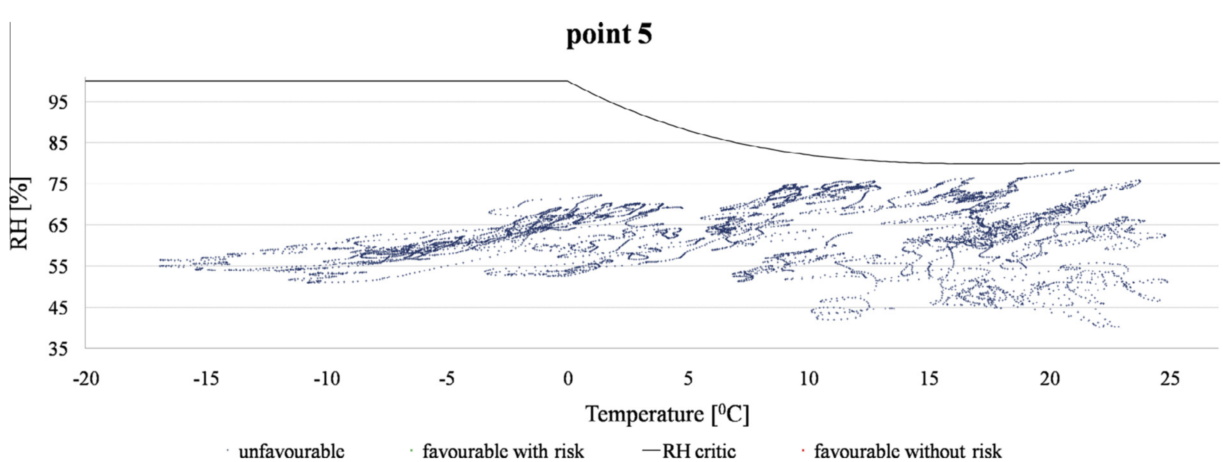

Fig. 6. Conditions for mould growth analysed during the period in point 5.

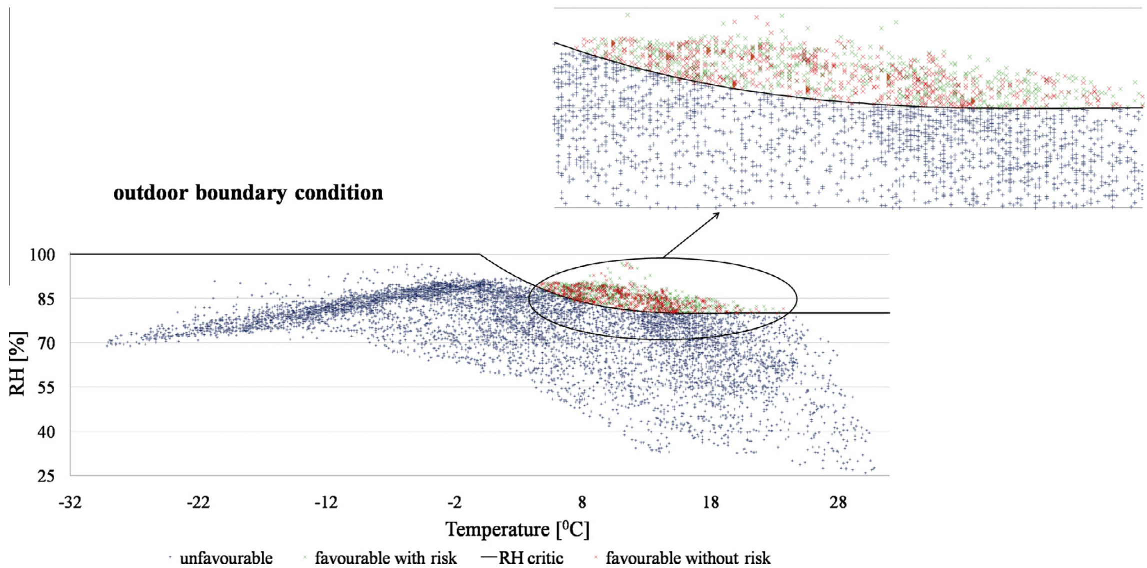

Fig. 7. Conditions for mould growth analysed during the period in point 6.

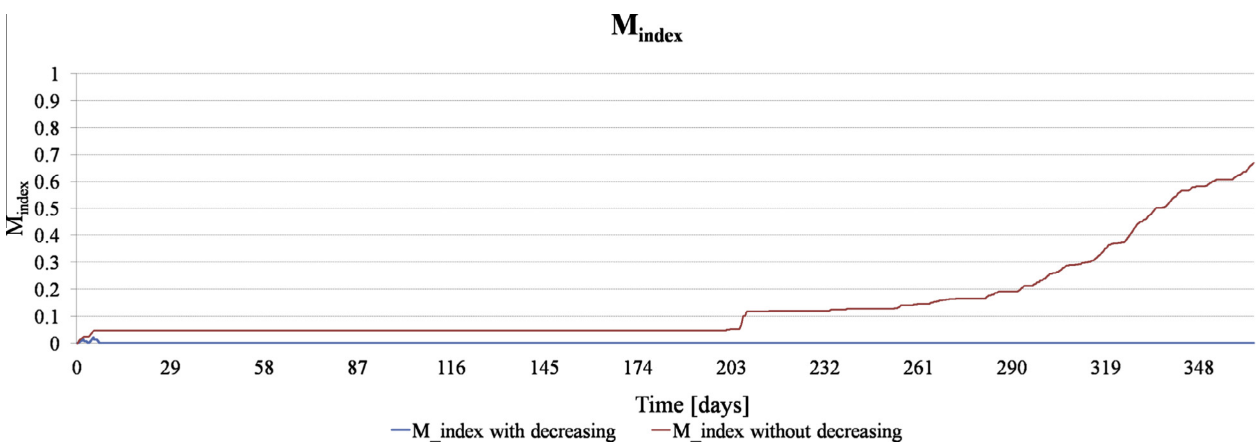

Fig. 8. Mould index analysed during period in the exterior boundary condition.

even further from the critic curve. The analysis simulates a whole year's temperature and humidity data, so there is no risk in the monitored points. In the next graph (Fig. 7), the situation on the exterior side of the analysed wall (point 6) is pictured. This represents the inside of the air layer, thus between the shield and the wooden cladding.

Point 6 already shows some risk for the mould growth. In Fig. 7, the red and green time step points are in the favourable area for the mould growth, which means there is a risk for starting of mould growth. The red coloured points show time steps where mould growth risk increases in favourable area and the green points determine cases where there is still a risk of mould growth, but the risk already decreases. The mould index progress is pictured in Fig. 8.

At the beginning of the solution the mould index increases a little, and then as conditions for the mould growth go down, the index showszero value and stays there for the rest of the solved period (1 year). If the decreasing process is not included in the solution, the mould index value reaches 0.621 during the period, which according to the defined mould growth rate is still not at risk level. So, the assumption is, there is no risk of moulds in the exterior wall. Therefore, no risk is evoked by unfavourable conditions for the mould growth during the analysed period.

We assume there might be risk of moulds on the real exterior side of the wall, i.e. that is on the outdoor surface of the wooden cladding which is directly connected to the weather conditions.

8. Conclusion

The low-energy house located in Oulu/Finland was subjected to mould growth analysis. Temperature and relative humidity data in the house have been measured since the end of 2009. Although measuring is considered to be the best way to obtain accurate data, sensors have shown a set of errors during the monitoring period. The missing or incorrectly measured data was replaced by data obtained with a HAM simulation performed by Wufi 2D. The computed verification showed small differences between measured and computed data. The error in the verification obtained is less than 2.8 °C in temperature values and less than 2.6% in the case of relative humidity. The verified data were used to analyse mould growth risk according to a theory published by Viitanen and Ojanen (2007).

The mould growth analysis was provided for a 1 year period from 31.7.2010 (11:00) to 31.7.2011 (11:00). The data in all the points were analysed. The temperature and relative humidity conditions do not show a risk of mould growing during the period. Closer to the exterior side of the wall, relations between temperature and relative humidity conditions are nearer to the critic relative humidity curve RH_{crit}, but still in the unfavourable area for the mould growth. The small percent of the time steps are located in the favourable area for mould growth in the air layer between shield and wooden cladding. However, these time steps do not affect the mould index value, if the decrease is considered.

According to the mould growth theory, there is no risk of moulds in the north wall of the presented low-energy house.

The presented paper illustrates a computing method for mould growth risk with the possibility to predict damages of the structure and/or health issues of inhabitants caused by moulds in future.

Acknowledgements

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References

Viitanen, H., Ojanen, T., 2007. Improved Model to Predict Mold Growth in Building Materials, Paper based on the VTT Projects “Building Biology” and “Integrated Prevention of Moisture and Mould Problems”, Finland.

Viitanen, H., Toratti, T., Makkonen, L., Peuhkuri, R., Ojanen, T., Ruokolainen, L., Räisänen, J., 2010. Towards modelling of decay risk of wooden materials, peer-00599240, European Journal of Wood and Wood Products 68, http://dx.doi.org/10.1007/s00107-010-0450-x.

Ojanen, T., Peuhkuri, R., Viitanen, H., Lähdesmäki, K., Vinha, J., Salminen, K., 2011. Classification of material sensitivity – new approach for mould growth modeling, Paper at the 9th Nordic Symposium on Building Physics – NSB 2011, Tampere, Finland.

Thullner, K., 2010. Low-energy Buildings in Europe – Standards, Criteria and Consequences, A Study of Nine European Countries, ISBN 978-91-85147-42-7, 2010, Lund, Sweeden.