Development of an improved model for mould growth: Modelling

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SUMMARY:

A large experimental study on 8 different building materials is going on in collaboration with the Technical Research Centre (VTT) and Tampere University of Technology (TUT), Finland. These materials are tested as pure materials and as a part of the building envelope constructions both in laboratory and outdoors. The laboratory tests are made partly under constant, but different conditions, and partly under varying conditions to simulate the effect of fluctuated wet, dry and frost periods. In the field exposures outdoors, the materials and constructions are tested under real conditions.

The main aim of this experimental programme is to use the measured results in the development of an improved model to predict mould growth. This improved model is based on an existing mathematical model developed on wood at VTT during 1990's. The focus in this new model is to extend the use for other materials and also for a greater variety of conditions.

This paper presents how the existing model is improved and also discusses the whole problem of modelling such a phenomenon. A sensitivity analysis of modelled mould growth and comparison with measured mould growth are also presented. The experimental set-ups and the results since 2005 from these extensive measurements on many different materials are presented more detailed in another paper to this conference.

1. Introduction

The requirements for durability of the buildings and indoor air quality are growing. Therefore the focus in hygrothermal modelling of whole buildings is moving towards a kind of risk analysis. One of the main risks in this sense is the mould growth and subsequent indoor air quality problems. More severe moisture problems can cause decay of the constructions. However, this paper concentrates on the mould modelling issue and predicting of mould growth. But what is more important, this paper also discusses the whole problem of modelling such a phenomenon. A sensitivity analysis of modelled mould growth and comparison with measured mould growth are also presented.

To understand the biological, chemical and physical phenomenon of the mould in building structures and modelling of it is challenging. However, approaches to model this kind of complex problem have been done and are still going on. The essential basis for a good model is a great amount of good measurements. A large experimental study on 8 different building materials is going on in collaboration with TUT and VTT, Finland. The studies and discussion in this paper are a part of developing of an improved mould growth model based on these experiments that are described in another paper to this conference (Lähdesmäki et al. 2008).

2. The nature of mould growth and modelling of it

The important starting point for the whole mould issue is to understand that mould spores are all over in our surroundings. Therefore we will never get totally rid of mould: The mould growth outdoors will always happen in our temperate climate, unless the building exterior surface is treated with fungicides and/or cleaned regularly. However, to provide durable and healthy buildings, we need to manage the conditions – especially the microclimate and the envelope constructions – in order to reduce the risk for mould growth. In this section, necessary conditions for mould growth are discussed shortly.

A certain **duration** of suitable exposure conditions is required before microbial growth will start. Particular emphasis is focused on this time period, the so-called response time or response duration in different humidity and temperature conditions for mould growth (Viitanen 1996, Hukka and Viitanen 1999). The lowest humidity level for mould growth is around RH 75 – 80 %. The response times have been proved to be short (from a few days to a few weeks) in pine sapwood in conditions favourable to the growth of micro-organisms and long (from a few months to a year) in conditions close to the minimum and maximum moisture or temperature levels. Critical humidity levels at different temperatures for mould growth as a function of duration time of exposure, are shown in Figure 1a.

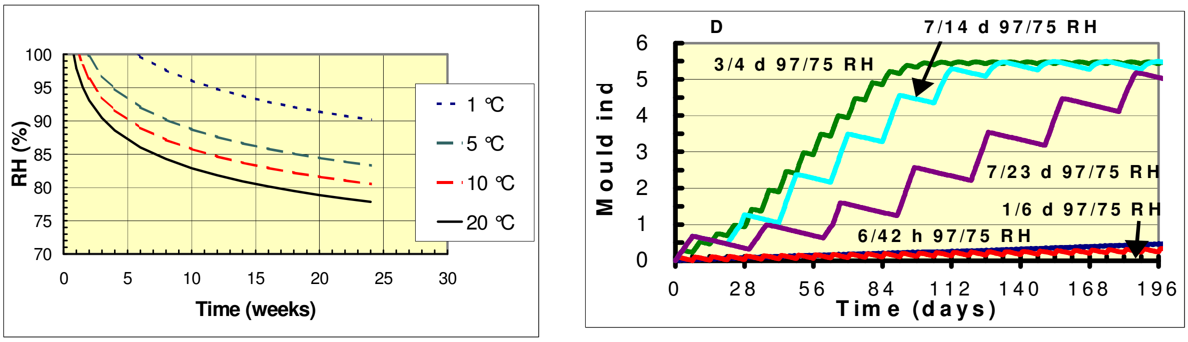

FIG. 1: a) Critical humidity (RH %), time (weeks) and temperature needed for the start of mould growth on pine sapwood (Viitanen et al, 2000). b) Impact of cyclically varying moist and dry periods on mould growth. Both figures are modelled, not measured.

Within fluctuating humidity conditions, the total exposure time for response of growth of mould fungi is affecting by the time periods of high and low humidity conditions as well as the humidity and temperature level. Short periods at high humidity conditions will not cause a fungal growth if the time periods at low humidity preventing mould growth are long enough (Viitanen and Bjurman 1995). When the period at high RH is longer than 24 hours, the effect of cumulative time at high humidity is more linear, but if the dry periods are very long, very low or neglected growth response can be expected. An exposure period at low RH prevents the growth and has a direct effect on the total response time required for mould growth. This is illustrated in Figure 1b.

In the simulation of mould growth it is crucial to know the lowest (threshold) conditions where fungal growth is possible in different material. Also the duration of these conditions is significant. There are certain minimum and maximum levels for moisture content of material (or water activity) or temperature between which fungi can grow in wood. Under these favourable conditions mould growth may start and proceed at different rates depending upon the interrelationship between humidity and temperature and upon other factors such as the organisms and the properties of the materials. There may exist different mould species but the mould index used is based on the growth activity of different mixed mould species. Different mould species depending on the conditions were found in the studies which were used as a data source for the modelling.

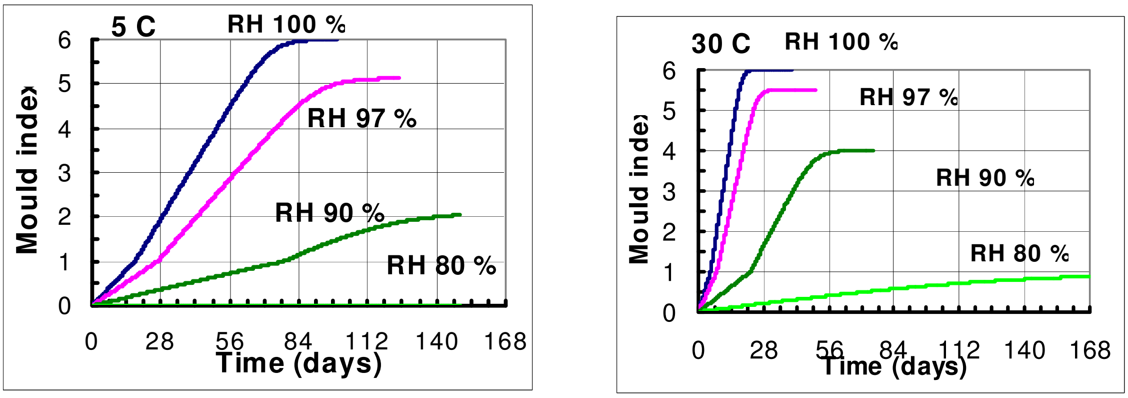

FIG. 2: The critical humidity, temperature and exposure time periods at varied constant conditions for initiation of mould growth on pine sapwood based on VTT mathematical mould growth model (Viitanen et al, 2000).

Time period needed for the initiation of mould growth and growth intensity are mainly regulated by water activity, temperature, exposure time and surface quality of the substrate. The experiments on pine sapwood material supported this theory and based on the results, a mathematical model was developed. The favourable temperature range for mould growth is 0-50 °C, and the critical relative humidity required for initiation and development of mould growth (mould index) is a function of temperature and exposure time (Figure 2).

3. Existing models for predicting mould growth

Two existing models predicting mould growth are presented below. The emphasis is on the models that are propably most comprehensive. Referring other modelling work is omitted here due to limited space.

3.1 VTT model

Mathematical modeling of mould growth has been a research topic at the VTT Technical Research Centre of Finland for many years. The research has included several experimental studies on conditions for mould growth primarily on wood, but also on other building materials. The experimental data has been used to create a mathematical model for mould growth. The present VTT model consists of a mathematical model that also takes into account the delay in mould growth rate due to the unfavourable conditions. There are different mechanisms for situations with delay:

a) the early stages (germination of spores),

b) too dry and too cold conditions and

c) the late stages of mould growth.

The model solves also the growth influenced by fluctuating humidity conditions. Equation (1) solves the mould growth index M as a function of time (weeks) t, temperature T, relative humidity RH, the wood species W (0 = pine and 1 = spruce) and the surface quality SQ from the drying process. k_1 and k_2 are coefficients expressing the delay in early and late stages of growth, respectively. These parameters and the model itself is described more detailed in (Hukka and Viitanen 1999) and (Viitanen et al. 2000).

$$\frac{dM}{dt} = \frac{1}{7 \cdot \exp(-0.68 \ln T - 13.9 \ln RH + 0.14W - 0.33SQ + 66.02)} k_1 k_2 \qquad (1)$$

The first version of this model was created as a part of a dissertation work, (Viitanen 1996), and it is based on a great number of measurements on pine and spruce. The mathematical model was generated with regression analysis of the measured data by Hukka and Viitanen for calculating the development of mould growth, which is expressed as mould index (Hukka and Viitanen 1999). The index is defined as in TABLE 1 and depends on if the growth can be detected using microscopy or visually. There may exist different mould species on a material, therefore this mould index is based on the growth activity of different **mixed** mould species.

TABLE 1: Mould growth index for the experiments and modelling (Viitanen and Ritschkoff 1991).

Index	Growth rate	Description
0	No growth	Spores not activated
1	Small amounts of mould on surface (microscope)	Initial stages of growth
2	<10% coverage of mould on surface (microscope)	
3	10-30% coverage mould on surface (visual)	New spores produced
4	30-70% coverage mould on surface (visual)	Moderate growth
5	> 70% coverage mould on surface (visual)	Plenty of growth
6	Very heavy and tight growth	Coverage around 100%

In the original model presented by Hukka and Viitanen (1999), the delay of mould growth occured only when the relative humidity was below 80% RH. Later the effect of low temperature has been also taken into account assuming that a simple delay process takes place also when temperature is below 0°C. However, the experimental research results from that phenomenon have been earlier limited.

In order to be able to analyse the critical humidity and temperature conditions in building constructions, this VTT model has been implemented in a hygrothermal simulation model TCCC2D (Ojanen et al. 1994, Ojanen 1996). This 2D model solves the transient heat, air and moisture transport fields of a structure that can consist of several material layers. The boundary conditions for the analysed structure can be, for example, hourly changing climate conditions and indoor conditions that have a set increase in humidity compared to outdoor conditions. Measured data can also be used as boundary conditions. The model solves the temperature and moisture content/ relative humidity value for every time step of the solution and for each node of the mesh representing the structure section. The mould growth index values can be solved for each node and the risk for mould growth in wood based or other organic (or soiled) material surface can be predicted.

Also, in a practical oriented moisture performance analysis of timber-framed exterior wall assemblies by Vinha (2007), this VTT mould growth model has been used to determine mould indices from hygrothermal calculation results carried out with WUFI-2D program (Künzel 1995).

At the moment, the model predicts only the mould growth for wood. However, wooden materials are among the most sensitive materials for mould growth and therefore the model can be used as a worst-case-scenario. Nevertheless, a research project to improve the model is going on as collaboration between VTT and TUT. The aim is to formulate a more diversified and improved application of the existing VTT model for mould growth. Some of the improvement aspects are:

- to develop reliability and range of use of the existing mathematical model in fluctuating temperature and humidity conditions
- to increase the number of material choices for the model
- to test usage of the model by doing experiments for structures and materials in laboratory and in field conditions, including the effects of adjacent material layers in a construction

3.2 Biohygrothermal model (WUFI Bio)

Sedlbauer (2001) has studied different models to evaluate spore germination and growth of different mould species on different type of materials. He found, that the isopleths based on artificial medium can be used to evaluate the growth rate of different fungi. He used a biohygrothermal model based on the relative humidity, temperature and exposure time needed for the spore germination of mould fungi based on the osmotic potential of spores. He analysed the effect of different climatic conditions on the spore moisture content and germination. He also evaluated the spore moisture content and germination time based calculated time courses of temperature and relative humidity in various positions of the exterior plaster of an external wall by implementing a model for mould growth in WUFI program (Sedlbauer & Krus 2003). The relationship between the different parameters in the biohygrothermal model is shown in Figure 3, i.e. a mould spore is given hygrothermal material parameters. This enables dynamic calculations, which again give the length and intensity of the conditions for mould growth based on critical limits for different type of materials (e.g. LIM I for bioutilizable substrates, such as wall paper, plaster board, building products made of biologically degradable materials, and LIM II for less bioutilizable substrates such as plasters and mineral building materials).

The time periods in the biohygrothermal model for spore germination are shorter than that of start of the growth (mould index 1) used in the VTT model. Also different type of material affect on the time periods needed for the spore germination.

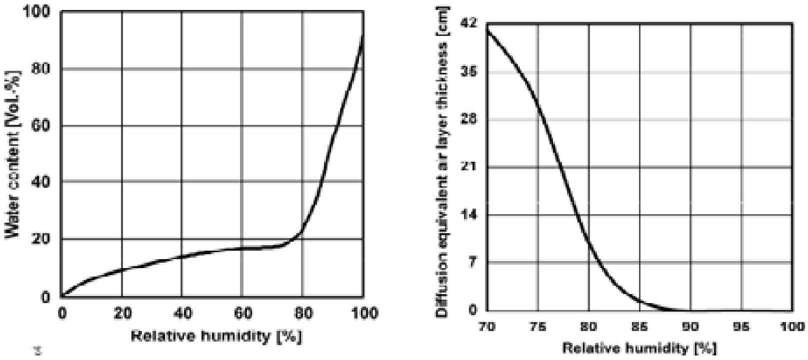

FIG. 3: Hygrothermal "properties" of a mould spore: The relationship between humidity and water content and diffusion resistance of the mould spore. (Sedlbauer & Krus 2003).

4. Sensitivity analysis - VTT Model

The following case study shows an example of how to use a mathematical model for predicting mould growth. The emphasis is on studying the effect of different assumptions on the resulting calculation result – the sensitivity analysis. The above described hygrothermal simulation tool TCCC2D, with the mould index calculation according to VTT-model is used together with field measurements. Also the biohygrothermal model implemented in WufiBio is used for some of the analysis for comparison.

The monitored temperature and humidity conditions from a field test of different building materials were used as boundary conditions for simulations when solving the mould growth for pine. These tests are part of the TUTand VTT collaboration project, still on-going and are presented in another paper (Lähdesmäki et al. 2008). The 48-hour-average values are shown in Figure 4. The detected mould growth level of pine samples were compared to those solved using different approaches for the mould index calculations. The period in focus is almost a year, starting in the summertime.

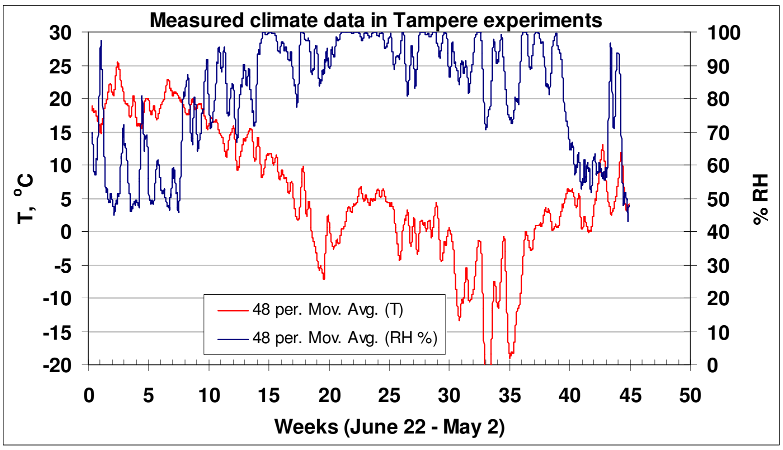

FIG. 4: Measured climate data presented using 48 hour moving average values. The simulations use the original hourly measured data.

4.1 Effect of modelling or not modelling heat and moisture capacity of materials

The first approach was to solve mould growth index for pine assuming that there is no delay between the outdoor and material surface conditions. The surface conditions of the material were assumed to be the same as those measured for the outdoor climate and there were no moisture or thermal capacity of the material that could have effect on the moisture balance. The possible error caused by this non-capacity simplification was compared with dynamic simulations with TCCC2D, where the solution for mould growth according to VTT model is integrated in the heat, air and moisture field solution.

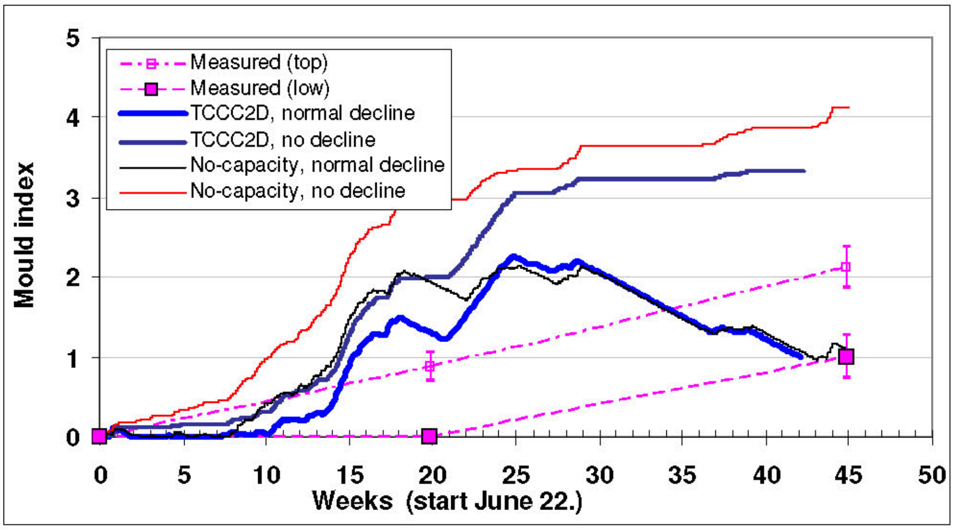

FIG. 5: Prediction of mould growth index of the wooden test board using measured climate data.Mould index was calculated using non-capacity and dynamic simulations (TCCC2D) with two different assumptions for decline of the mould growth. Measured (top) and (low) mould indexes stand for detected growth on the upper side and lower side of the sample. The upper side is exposed for soiling.

The results are seen in Figure 5 together with 2 different assumptions for decline of the mould growth within the model: No decline of mould index or normal decline: If the conditions are not favourable for mould growth – they are too dry or too cold – the mould index will decline according to a certain rate. The model used for decline is based on the measurements under relatively short period (days rather than weeks) dynamic condition cycles and it is meant to represent the delay in the starting of mould growth after a period of unfavourable conditions for the growth. It is obvious that this assumption cannot be totally correct for varying cases, especially for seasonal changes. This is one item that will be solved in the pending project.

The difference between the no capacity -model and dynamic simulations was significant during the first 20 – 22 weeks of simulation. The no capacity -approach predicted mould growth index 1 about two weeks and the level 2 in about 5 weeks before the dynamic solution. Only when the material had reached high enough moisture content, the two solutions had about the same mould growth level. The studied assumptions for decline – no decline vs. decline – gave results where the detected mould index corresponds best with a result which is between the no-decline and normal decline approaches.

4.2 Effect of initial moisture content and convection

The effect of initial moisture content of the material (80 % RH or 65 % RH) was also studied. It did not have any effect on the mould growth. If the conditions had been suitable for mould growth, already in the beginning of the simulation the initial moisture content level could have had some effect on the mould growth.

The moisture transport coefficient of the surface has an effect on the surface conditions and thus also to the mould growth. The case was studied using two different mass transfer coefficient levels: normal convection (with convective heat transfer coefficient 4.0 W/Km^2) and low convection (1.5 W/Km^2). The mass transfer coefficient is solved from the convective heat transfer coefficient.

The results showed a clear effect of surface moisture transfer coefficient on the mould growth of the material surface. With low convection the moisture transport into the material is lower and thus the surface conditions are more stabile under dynamic conditions than with high convection. This leads to lower mould index, in this case. The situation is opposite in a drying situation: If the convection is low, the conditions for mould growth will stay favourable for a longer period and the mould growth index will be higher.

5. Discussion

Prediction of mould growth, however, is always only predicting the risk and not the exact growth. The influence of the uncertainties, whether it is the model itself or e.g. the weather data, is significant. Figure 6 presents partly a comparison of two totally different models – WufiBio (Sedlbauer & Krus 2003) and VTT Model – and partly influence of weather data. In Figure 6 all cases but *"VTT model, normal decline, Espoo climate"*, are determined for measured storage room data, where samples of pine sap wood were exposed to outdoor conditions plus some humidification. *Espoo climate* is normal weather data measured for same period for some 150 km away. As a material class for prediction of mould growth was used pine sapwood (VTT model) and LIM I (Wufi Bio).

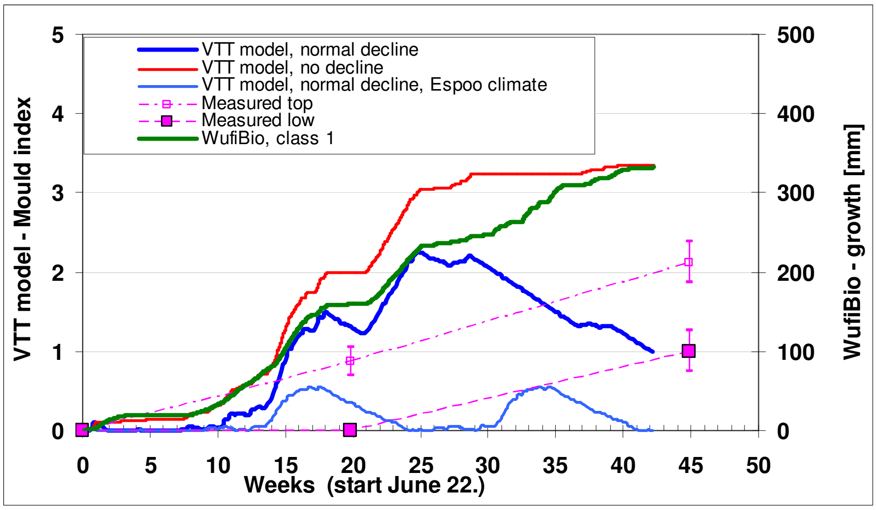

FIG. 6: Comparison of VTT Model and WufiBio – and measured mould index – on pine sap wood. Results with VTT Model have been calculated under several assumptions. "VTT model, no decline" is assumed to most comparable with the biohygrothermal model behind WufiBio.

The comparison of the results shows how sensitive the calculations are. VTT model without decline corresponds relatively well with the biohygrothermal model (Figure 6). This is logical, as the assumption also in the biohygrothermal model is that there is no decline, when the conditions are unfavourable for mould growth. However, there is a difference in the growth rate, especially during longer periods of very high RH: The VTT model predicts here higher growth rate than the biohygrothermal model. The temperature in these periods varies roughly from +10ºC to 0ºC. In contrary, when the temperature stays below zero, the mould growth rate according to biohygrothermal model is still active, while it is practically stopped according to VTT model. Nevertheless, this is a very simplified approach for an explanation as the models include several parameters that have effects in various directions. Yet another source for uncertainty and deviation for the results when predicting mould growth with any model is the choice of the critical level of e.g. temperature and humidity conditions. These conditions vary a lot depending on the material itself. In addition, any soiling during the time will change the sensibility of the surface for mould growth. Therefore, prediction of mould growth with calculations must always be assessed with expert knowledge on the nature of mould growth.

There are several aspects that have to be taken into account in the interpretation of the experiments and analysis of the mould growth levels: Under **dynamic tests** the conditions at the interface of the air and test sample are typically different than the air conditions adjacent to the test sample. Therefore it may cause errors if the measured dynamic climate conditions are used as the critical surface conditions. Even in constant conditions the **initial moisture content** of the test material should be known and reduced from the measured data. Under dynamic conditions the thermal and moisture **capacity** of material and the heat and mass **transfer coefficients** on the surface may cause a severe delay in the change of surface conditions, differences in the humidity level and in the mould growth when compared to the adjacent conditions. Dynamic simulation that solves the surface conditions should be used both in the analysis of dynamic mould experiments and when predicting the mould growth in structures under real climate conditions. The use of full simulation enables to separate the delay in the actual mould growth from the delay in the surface conditions. The existing VTT-model has **declination of**

mould index when the conditions are not suitable for growth. The origin was to model the delay of mould growth during the short period dynamic conditions (some days). This declination seems to be artificial and probably not proper to adopt in seasonal conditions. New seasonal experiments should provide information about the mould growth during and after too dry or cold conditions, which enables the improved modelling of the phenomena.

6. Conclusion

This paper has taken up the issue of modelling mould growth in building envelopes. There exist some model developments in different research institutions. Among them, there exists some kind of consensus about the overall criteria for mould growth as a function of temperature, relative humidity and time. Nevertheless, there is very little knowledge on mould growth on different kind of materials and effects of the aging of materials, coatings and dust accumulation on the mould growth.

The mould growth model can be used to study the risks for mould growth on (wooden) material surface when the surface conditions (temperature and relative humidity) are known. Typically the conditions vary dynamically and their hourly values should be known to be able to study the mould growth. Long period (daily, weekly. etc.) time averaged values may not show the risks of the actual conditions, i.e. the peak humidity levels etc. on the mould growth. The same kind of error may be caused when the adjacent climate conditions are used as critical conditions instead of the actual surface conditions. Therefore the effect of the structure and material should always be taken into account when solving the critical conditions for the mould growth.

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