SIMPLE SURFACE CLIMATE MODELS FOR MODELLING MOULD GROWTH ON WOODEN FAÇADES

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ABSTRACT

The weathering of wooden surfaces is caused by mould growth and lignin deterioration. For well insulated buildings, the effect of the interior climate is small and sometimes negligible.

This paper describes two simple models for surface temperature and moisture on a wooden façade for use with mould growth models. The models are driven by exterior climate data combined with ray-tracing to account for the micro scale variations of the solar irradiance on the wall. The simplified models are compared to HAM simulations and measurements of temperature and humidity (RH) in the wall of a highly insulated wooden building.

INTRODUCTION

New developments in architecture are moving towards less surface treatment, and more use of uncoated wood surfaces in façades. Uncoated wood is naturally weathered or colored by climatic exposure. It is commonly known that mould growth is directly controlled by the climate which the wood is exposed to, where humidity and temperature are the main drivers of mould growth on a specific material. The temperature and moisture conditions on an exterior wall will have large variability. A windowsill protruding only a few centimeters from the wall will create a zone on the wall which is shaded from solar radiation and driving rain. On such facades, the variation of the exterior micro scale climate might be more important for the mould growth than the heat and moisture transport through the wall. The term “climate” is often described as the average of meteorological conditions. The diurnal dynamics of the climate of a wall will have large variations. When a façade is exposed to a glimpse of direct sunlight for some minutes, the temperature on the surface rises immediately due to the absorption of the solar radiation and can be 10-30 °C higher than the air temperature. Micro scale climate is usually described to have a time scale of seconds to hours whereas macroclimate is described with a time scale from half a day to a week. In the application of mould growth models to exterior façades it appears that the microclimatic conditions will have to be applied to organisms that we up to now study with a macroclimatic approach.

Another limitation to existing mould growth models is that they are use ambient values for temperature and humidity in controlled laboratory environment. In outdoor environment however, there is large variation of potential mould growth on the façade of a building, as can be seen in Figure 1. The surface conditions of the wooden cladding can be simulated by Heat and Moisture (HAM) simulations, taking into account indoor and outdoor climate as well as the physical properties of the wall. The surface conditions can thus be applied in a mould growth model, as shown in Thiis et al. (2015).

It is a general view that the expected climate change will increase problems with mould growth on building façades. However, since the dynamics of mould growth with varying climate is not fully understood, the extent of the foreseen problems are not yet quantified.

Figure 1. Colour differences on a partly shaded façade.

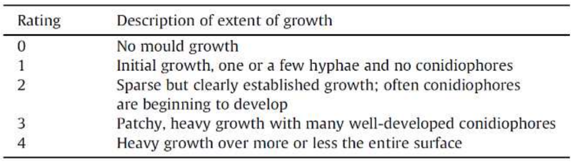
MODEL DEVELOPMENT

Mould growth on wood

Several authors have described and developed models for mould growth on various materials; for example the isopleth systems, biohygrothermal model, empirical VTT model, mould growth indices, time-of-wetness (Adan 1994, Ayerst 1969, Hukka & Viitanen 1999, Johannsson et al 2010, Krus et al 2007, Sedlbauer 2002). These models include the main influencing factors for mould growth: the surface temperature and air relative humidity (RH), and they are based on either experiments or assumptions. Some of these models do not include the variation in exposure time which is also a very important factor when predicting mould growth. Gobakken et al. (2010) proposed probability models for mould growth on exterior surfaces based on the number of hours the relative humidity (RH) was higher than 80% concurrently with temperature higher than 5 ^{0}C. There is yet no mould growth model known to the authors, which uses the moisture content of the wood directly. This obvious shortcoming makes is difficult to apply mould growth models on exterior surfaces which are heavily exposed to driving rain.

Thelandersson & Isaksson (2013) proposed a mould resistance design (MRD) model based on a dose –response relationship, where onset of growth can be predicted by combining relative humidity and temperature for any given climate. The model uses only the air relative humidity and the air temperature, thus partly omitting the actual conditions within the material which mould grows on. This simplification permits the use of the simplified models proposed herein. The MRD-model is controlled by a basic parameter in the form of a critical dose D_{crit}, which depends on the substrate or material surface on which growth may take place. Planed spruce in a climate with 90% RH and T=20 ^{0}C corresponds to a D_{crit}=39 which is used in this study. Separate doses for moisture and temperature are computed using 12-hour mean values of ambient temperature and ambient relative humidity in controlled laboratory environments, and the total dose is a combination of these two doses. Warm and wet conditions (T > 0.1°C, RH > 75 %) yield a positive total dose, whereas conditions that are unfavorable for germination and mould growth (RH > 75% and/or T < 0.1°C) yield negative doses. The MRD model simulates the growth process up to the limit state of onset of mould growth, and is therefore only valid up to rating 2 "sparse but clearly established growth". However, as pointed out by the authors, model response above this level can be looked upon as a measure of how the limit state is exceeded, but should not be compared to further growth and the development of established mould. The mould rating scale is shown in figure 2.

Figure 2. Mould rating scale (Thelanderson & Isaksson (2013)



Rating	Description of extent of growth
0	No mould growth
1	Initial growth, one or a few hyphae and no conidiophores
2	Sparse but clearly established growth; often conidiophores are beginning to develop
3	Patchy, heavy growth with many well-developed conidiophores
4	Heavy growth over more or less the entire surface

Surface temperature.

The one-dimensional Fourier's law, $q_x = -k\frac{dT}{dx}$, describes the heat flux in a material. Here q_x [W/m^2] is the heat flux in the x-direction, k is the thermal conductivity and T is temperature.

In numerical simulations of fluid and mass transfer, it is often necessary to know the wall surface temperature. This is commonly found by applying a special case of Fourier's law called the Heat Flux Boundary Conditions in which the surface temperature of a body is determined by:

$$T_w = \frac{q_{room}+q_{stored}-q_{rad}}{h} + T_a \qquad (1)$$

Here T_w is the wall surface temperature, q_{room} is the heat flux from the interior trough the wall, q_{rad} is the radiative heat flux from the surroundings, q_{stored} is the heat flux caused by heating or cooling the material in the wall, *h* is the local heat transfer coefficient and T_a is the temperature of the fluid near the surface. In the example shown later in the paper, the effect of convection within wall cavities is excluded.

In situations with little or no radiation from the surroundings, i.e. when the sun is down, q_{room} can be found by

$$q_{room} = \frac{dT_{wall}}{R_{wall}} \qquad (2)$$

Where R_{wall} [m^{2}K/W] is the thermal resistance of the wall. In a common, modern buildings q_{room} is in the order of 3 to 10 W/m^2 in a cold climate. Since the solar irradiance often will be in the range of several hundred W/m^2, q_{room} will be negligible during hours when the sun is over the horizon.

The heat flux from stored thermal energy in the building material, q_{stored} can be found using

$$q_{stored} = \frac{cm\mathrm{d}T_{t\_wall}}{At} \qquad (3)$$

where c [J/kgK] is the specific heat capacity, m [kg] is the mass of the wall material contributing and dT_{t_wall} [K] is the temperature change of the material over a specific time t [s] and A [m^2] is the unit area of the wall. This means that q_{stored} is 0 as long as there is no change in temperature of the wall material. For a wall with a ventilated wooden cladding of thickness 20 mm where only the cladding contributes to the q_{stored} and with density of 455 kg/m3 and specific heat capacity c=1500 [J/kgK] which the temperature changes 5 degrees in one hour, the heat flux will be 1500[J/kgK]*(1[m]*1[m]*0.02[m]*455[kg/m^3])*5[K]/1[m^2]*3600[s]≈18 [W/m^2]

The solar radiation, q_{rad} is usually measured on meteorological stations, and will in cases with no cloud cover also be possible to estimate based on solar position and standard atmospheric conditions. It is important to note that the radiative heat flux on a surface should be corrected for the reflected amount of the radiation. q_{rad} is therefore $q_{rad}=\alpha q_{solar}$ where α is the absorption coefficient of the surface material.

The geometry of a building is also important when determining the radiation on the cladding. The solar radiation distribution on a wall is subject to local shading which will change with the position of the sun during the course of the day. Accurate information about the solar radiation on the façade at every point in time and space is therefore necessary to simulate the surface temperature and thus the growth conditions of mould on the surface.

Surface moisture and relative humidity (RH)

Some façade materials are porous and can store water in its pores. However, most mould growth models use the relative humidity in the air and not the moisture in the material as argument. In a controlled climate with little variation in a laboratory, this is a good estimate, but in a natural environment where the variation is larger, this will no longer be valid. Wood will reach its equilibrium moisture content (EMC) after a given time in air with a specific RH. The time it needs to reach EMC is dependent on RH, temperature and wood substrate. Mazzanti and Uzielli (2009) reports that an unpainted poplar wood panel subjected to a change in RH from 85 to 42% at a temperature of 30 degrees, loses 26% of the total desorbed water within the first hour. This is of course dependent on the surface to volume ratio of the sample, but indicates that the moisture content in wood is very sensitive to the sudden variations in environmental exposure.

The relation between temperature, water content and RH is important in meteorological forecasting and is studied by several authors. The Clausius–Clapeyron equation characterizes the phase transition of water as temperature and pressure changes. The August-Roche-Magnus approximation gives a good approximation of this equation and Bolton (1980) gives a set of coefficients for the approximation where RH is found from:

$$RH = 100\frac{\exp(\frac{aT_d}{b+T_d})}{\exp(\frac{aT}{b+T})} \tag{4}$$

Here T is the air temperature, a=17.67, b=243.5 and T_d is the dew point temperature given by

$$T_d = \frac{b[\ln\left(\frac{RH}{100}\right)+\frac{aT}{b+T}]}{a-\ln\left(\frac{RH}{100}\right)-\frac{aT}{b+T}} \tag{5}$$

Assuming that the air in the boundary layer has the same absolute water content as the ambient air and that the temperature on the surface of a building is varying with the parameters given in the previous section, the RH in the boundary layer can be found by combining equations (5) and (4), substituting ambient air temperature T_a for T in eq. (5) and substituting T_w for T in eq. (4). I.e. the dew point T_d is calculated for the ambient air and RH is calculated using the dew point and the modeled surface temperature from equation (1).

Micro climate and solar radiation

The model for surface temperature outlined above needs input of the solar radiation on the façade in time and space to run. The software tool RADIANCE has been developed to simulate the radiation in illuminated spaces. It uses the technique of ray-tracing, which follows light backwards from the image plane to the source. RADIANCE and another daylight simulation engine, DAYSIM (Reinhart and Walkenhorst, 2001), has been incorporated in the software DIVA-for Rhino, which provides a user friendly input to the simulation engine. The software has been used to calculate the climate-specific hourly irradiation at nodes located on the façade of a 3D digital building model. The software uses the well-known .epw (EnergyPlusWeather) files that provide hourly weather data for more than 2000 locations in the world.

Using a relatively dense simulation grid with one node every 10x10 cm gives the possibility to simulate the shading effects of small features like window-sills protruding 10 cm from the façade as well as the lager effects as shading roof eave and inside corners. The software calculates the hourly solar radiation in every node for one whole year given the climate and the geographic position of the building.

VALIDATION

Wood is heterogeneous in structure and constantly in a state of changing (i.e. shrinking, swelling, degrading). Traditional resistance based moisture sensors are sensitive to development of cracks in the wood, chemicals from air pollution, orientation of annual year rings, temperature and moisture gradient. In this study, a 1D-Heat And Moisture (HAM) numerical simulation software is used to validate the calculated surface conditions of the façade. The 1D HAM simulation tool used in the study is the well-documented WUFI from Fraunhofer Institute. This tool calculates the transient behavior of heat and moisture in a multi-layered wall and has been extensively validated by e.g. Antretter et al. (2010).

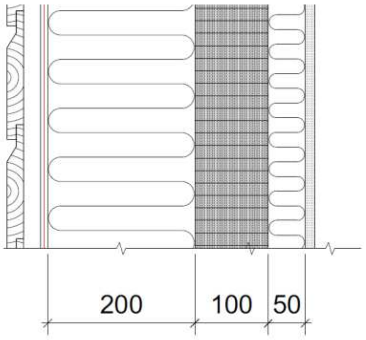


Figure 3. Section of wall in validation case, consisting of 200+50 mm mineral wool and 100 mm massive wood

Figure 3 shows the validation case which is a well-insulated massive wood wall situated in Norway. The wall consist of 200+50 mm mineral wool and 100 mm massive wood with a total thermal resistance is R_{wall} = 8.3 [m^2K/W] and is used to validate the simplified models described herein. The wall has an air layer behind the cladding, which is treated as a simple heat resistance, disregarding air convection.

RESULTS AND DISCUSSIONS

Figure 4 shows the performance of the simple models for surface meteorological conditions compared to the more sophisticated simulations with WUFI. The simulation case is a south facing wall constructed as in Figure 3 and the simulation period is 10 days during summer with relatively large solar irradiation. The figure shows good agreement between the two models and that the solar radiation is a very important parameter for both the surface temperature and the surface RH. However, because of the exclusion of the convection effect within the wall cavity in both models, this must be regarded an idealised case.

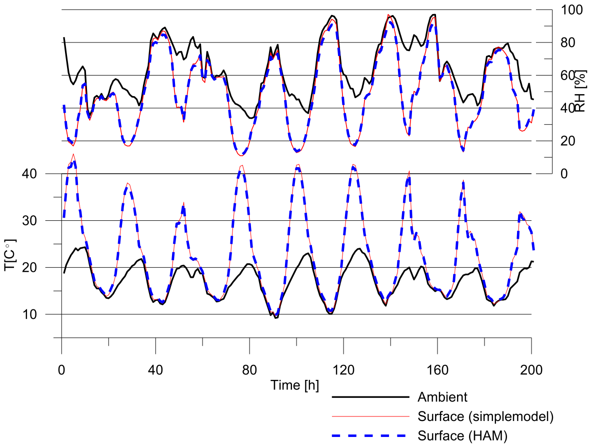


Figure 4. Comparison of surface conditions simulated with the WUFI and the simple models presented herein together with ambient conditions.

The site where the models have been applied to is Jersey in the English channel. The climate here is has relatively high decay hazard according to Brischke et al. (2011). Using the 12 h meany weather data as input to the MRD-model of Thelanderson & Isaksson (2013) gives the impression that this site is largely affected by mould growth, especially from late spring. Figure 5 shows the mould growth rating over a year at the site.

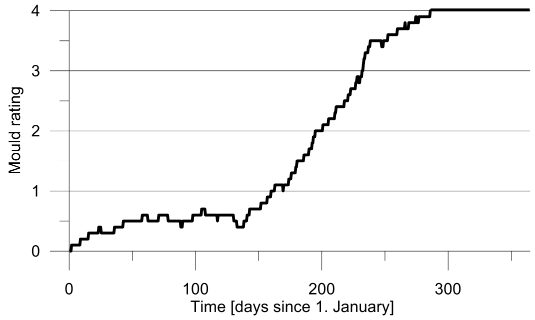


Figure 5. Mould rating using ambient weather at Jersey calculated by MRD-model using $D_{crit}=39$.

A more detailed simulation of the micro scale meteorology reveals that a façade in the same climate has very different mould growth conditions. Figure 6 shows the yearly mean solar radiation on the south facing façade of a 3D model house. The solar radiation is simulated with the software DIVA for Rhino and the model is taken from 3D warehouse in SketchUp. The distance between the nodes is 10 cm in both X and Z direction, making the total number of nodes in the simulation is close to 10.000. The solar radiation has a large variation caused by local shading from secondary building parts. Some parts recives very little solar radiation, indicating that it is being shaded for large parts of the year. Using the solar radiation with a radiation absorption coefficient α=0.4, corresponding to untreated spruce, and the ambient temperature as input to eq. (1), it is possible to calculate hourly temperatures for all the nodes.

Figure 5. Yearly mean solar radiation on a south facing façade on Jersey

Figure 7 shows the annual mean surface temperature on the façade of the building. Even if this is a south facing façade, the variation in temperature is large, ranging from X to Y °C. The surface temperatures, ambient temperature and ambient RH are all used as arguments in eq. (4) and (5) to calculate the boundary layer RH shown in figure 8. Since both the surface temperature and the boundary layer RH are directly dependent on the solar radiation, the variation patterns of the three parameters are similar.

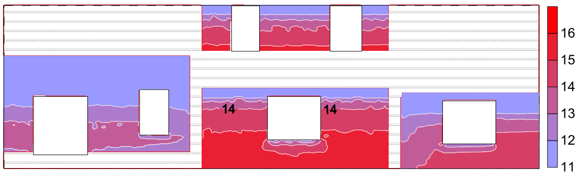


Figure 7. Mean annual temperature on a south facing wooden façade on Jersey.

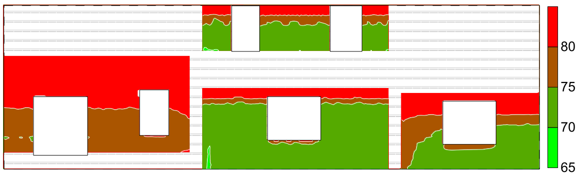


Figure 8. Mean annual RH in boundary layer of a south facing wooden façade on Jersey.

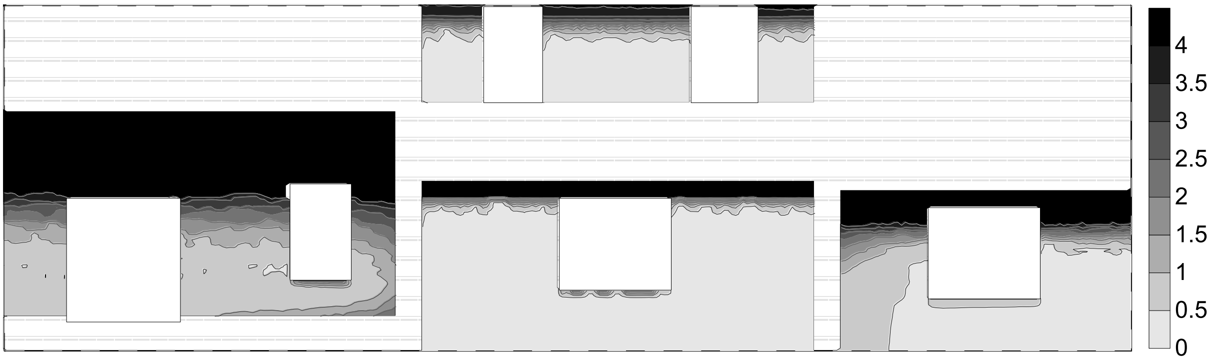


Figure 9. Mould rating on south facing wooden façade in Jersey

Using the 12 h mean temperature and RH on the façade as input to the MRD-model of Thelanderson & Isakson it is possible to calculate the dynamic development of the spatial distribution of mould on the façade. Figure 9 shows this distribution after one year of exposure to the climate. The main parts of the façade is not affected by mould at all and only the scaded parts has mould growth. In the area beneath the eaves the mould rating is 4 which is the maximum of the rating scale. Also the window sills, extending 10cm from the façade, have shading effect large enough to affect the mould growth. Note that this method does not include neither driving rain nor nighttime overcooling and condensation. These two meteorological effects are expected to have large influence on the moisture conditions of a wooden façade. In some climates driving rain is the main source of moisture on a façade, and since wood is a porous material which can store moisture for a long time, driving rain might have a larger effect than the drying effect of the solar radiation. Simulation of driving rain is a topic which is in development, and it would be beneficial for the accuracy of mould growth modeling on external façades to include this reseach.

The effect of wind dependent heat transfer coefficient (h in equation 1) on the mould growth conditions on an external wall is shown in Thiis et al. (2015). They showed that wind is an important parameter, at least on the parts of the building that is less exposed to solar radiation. The work suggests that wind dependent convective heat transfer coefficient should be included in a model for exterior mould growth.

CONCLUSIONS

This study has shown the importance of accuracy and spatial resolution of meteorological data when modelling mould growth on external façades. Simply using data from a standard meteorological station will provide estimates of mould growth, which are very different from estimates using the meteorological conditions on the surface. Since the growth dynamics of mould is dependent on the variations of temperature and climate, a mean increase in temperature and humidity due to climate change is not necessarily associated with an increase of mould growth. This study shows that, at least for a façade exposed to solar radiation, the building shape and associated shaded zones are determining the mould growth. In areas with less solar exposure, the mould growth is less dependent on the shape of the building

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