A new Model for Mould Prediction and its Application in Practice

K. Sedlbauer & M. Krus
Fraunhofer-Institute for Building Physics, Holzkirchen, Bavaria, Germany

ABSTRACT: In buildings growing conditions for mould fungi can occur and cause fungus infestation. The danger for the occupants of dwellings lies in the production and spreading of pathogens (disease causing agents). Therefore, consequent measures have to be taken to avoid health dangers that come from mould fungi in buildings. In order to avoid the mould fungus formation, a strategy has to be set up that focuses on the growth conditions for mould fungi. The most important boundary conditions for the growth of fungi are temperature, humidity and substrate conditions which have to be simultaneously available over a certain period of time. A new biohygrothermal procedure is developed, which allows the prediction of mould growth under transient boundary conditions. This new method is described and its application is demonstrated on different practical examples.

1 INTRODUCTION

In order to avoid the mould fungus formation in buildings, a strategy has to be set up that focuses on the growth conditions for mould fungi and also considers the complex transient processes of building physics. The application of biocides is always accompanied by additional health risks, especially when used indoors, and moreover can prevent the formation of mould fungus only over a limited period of time. A prerequisite for preventing mould fungus without the use of biocides is the knowledge of the boundary conditions under which fungus growth takes place. In reference to the boundary conditions for the growth of fungus it turns out that the decisive parameters of influence like temperature, humidity and substrate have to be available over a certain period of time (Ayerst 1969; Adan 1994) simultaneously in order to enable the formation of mould fungi. Therefore, the main focus of this scientific paper on hand is to develop a planning instrument from the point of view of an engineer that aims at predicting the formation of mould fungus. This procedure consists of two consecutive predictive models, i.e. the Isopleth model and the transient Biohygrothermal model.

2 GROWTH CONDITIONS FOR MOULD

German literature often states a relative humidity of 80% at wall surfaces as the decisive criterion for mould growth, independent of temperature. Sometimes it is mentioned that many types of mould can also thrive at lower humidities (see for example the new draft of DIN 4108-X, Mould (Deutsches Institut für Normung 1999)). Other growth conditions, namely a suitable nutrient substrate and a temperature within the growth range are taken for granted on all types of building elements usually.

The growth conditions for mould may be described in so-called isopleth diagrams. These diagrams describe the germination times or growth rates. Beyond the lowest line every mould activity ceases, under these unfavorable temperature and humidity conditions spore germination or growth can be ruled out. The isopleths are determined under steady state conditions, i.e. constant temperature and relative humidity. The three factors required for growth – nutrients, temperature and humidity – must exist simultaneously for a certain period of time; this is the reason why time is one of the most important influence factors.

3 ISOPLETH SYSTEMS

Significant differences exist among the various fungus species. Therefore, when developing common Isopleth systems all fungi were regarded that can be detected in buildings. Quantitative statements on the growth prerequisites temperature and humidity will be set up for these more than 150 species that fulfil both features, as far as they are given in literature. To further clarify the differentiation of the life phases of the mould fungi, the data for spore germination and myzel growth will be given separately.

Within the Isopleth model the prerequisites for the growth of mould fungi in dependence of temperature and relative humidity are stated for the above mentioned hazardous classes at first for the optimal culture medium. The Isopleth systems were developed for assessing the spore germination as well as the growth of the myzels. They are based on measured biological data and also consider the growth prerequisites of all fungi of one hazardous class. The resulting lowest boundary lines of possible fungus activity are being called LIM (Lowest Isopleth for Mould).

In order to regard the influence of the substrate, that is the building materials or possible soiling, on the formation of mould fungus, Isopleth systems for 4 categories of substrats were suggested that could be derived from experimental examinations (Block 1953; Grant et al. 1989). For this purpose four categories of substrats were determined and different building materials assigned:

Substrate category 0: Optimal culture medium

Substrate category I: Biologically recyclable building materials like wall paper, plaster cardboard, building materials made of biologically degradable raw materials, material for permanent elastic joints;

Substrate category II: Biologically adverse recyclable building materials such as renderings, mineral building material, certain wood as well as insulation material not covered by I;

Substrate category III: Building materials that are neither degradable nor contain any nutrients.

An individual Isopleth system will only be set up for the categories 0, I and II, whereas in the building category 0 the Isopleth systems for optimal culture media are applied (Fig. 1). For the substrate category III no Isopleth system is given since it can be assumed that formation of mould fungi is not possible without soiling. In case of considerable soiling, substrate category I always has to be assumed. The basic principle of the new method and of defining the building material categories is to assume a worst case scenario, therefore always being on the safe side in respect of preventing the formation of mould fungi. To what extent correcting the Isopleth systems for individual building material categories towards increased relative humidity can still be done with a clear conscience, has to be proved by further measurements.

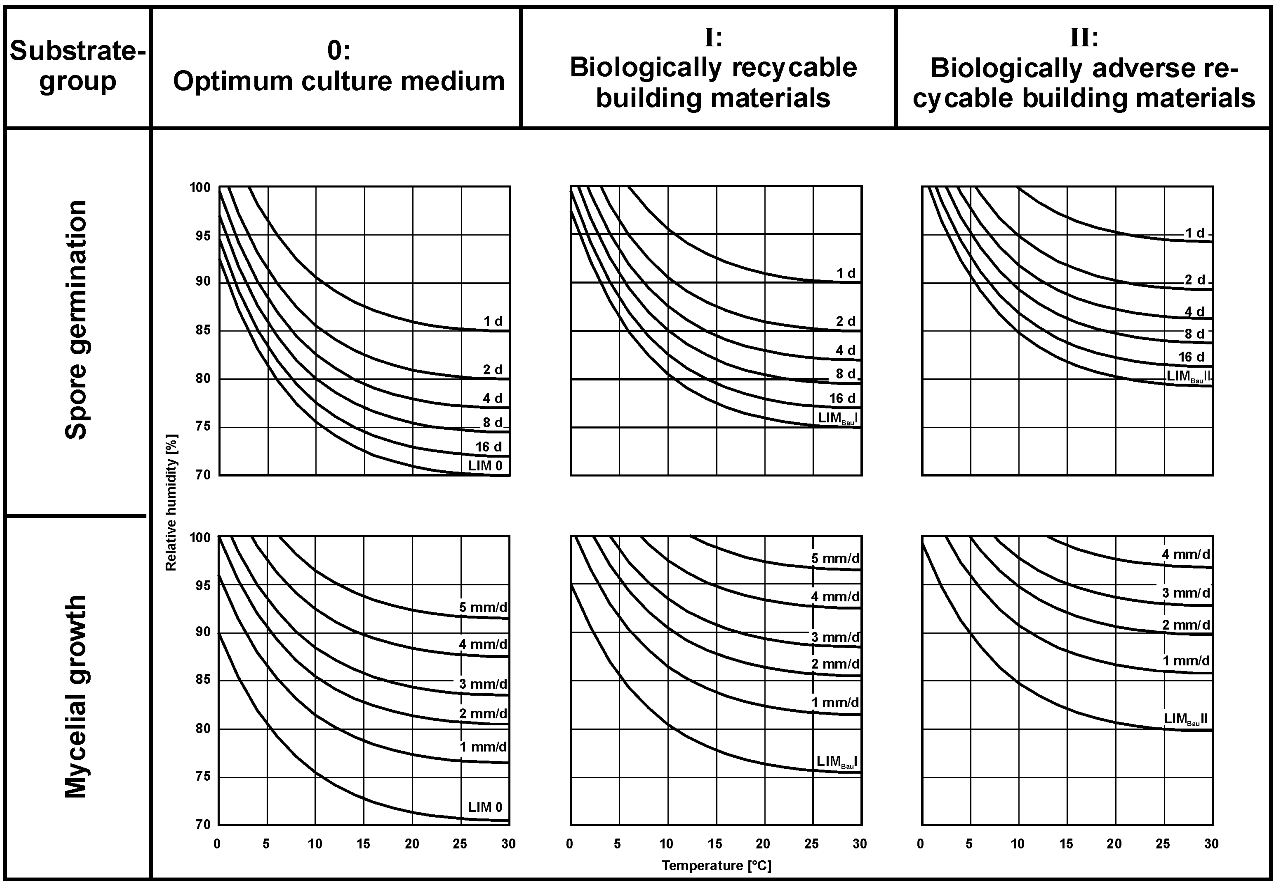


Figure 1. Isopleth systems for 3 categories of substrats, in order to regard the influence of the substrate on the formation of mould fungus (Sedlbauer 2001).

In order to differentiate the mould fungi according to the health dangers they may cause, a so called hazardous class K will be defined as follows (Krus et al. 2002): The Isoplethsystem K applies to mould fungi, which are discussed in the literature because of their possible health effect (Fig. 2). For these species (Aspergillus fumigatus, Apergillus flavus and Stachybotrys chartarum) growth data from (Sedlbauer 2001) are available. The Isoplethsystem for the fungi estimated as critical is based on the available data on optimum culture medium. To make a adequate substrate specific isopleth the precise measurements are missing. To move the isopleth to a higher humidity analogically to the development of the imagined buildingmaterial isopleth, is too risky especially for these fungi according to today's knowledge.

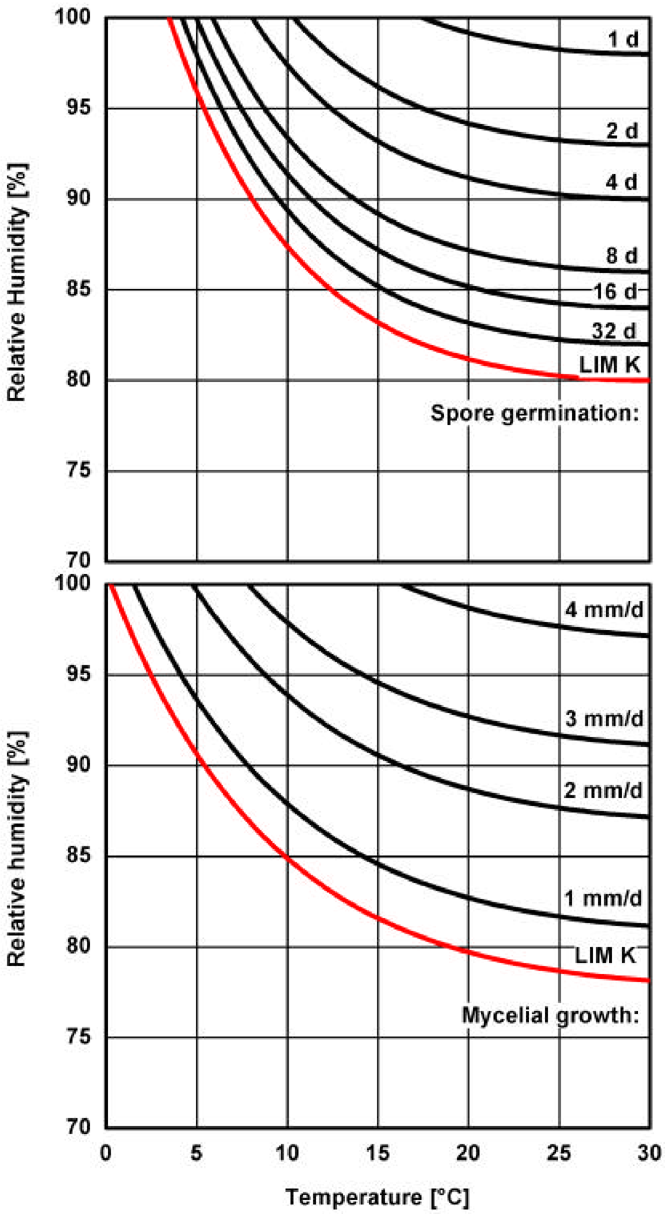


Figure 2. Isopleth systems for the so called critical fungus species (Künzel 1999).

Altogether, the following four Isopleth systems were developed for the spore germination and for the growth of the myzels individually. Every one of the systems is valid for a whole group of mould fungi and takes into account, next to optimal culture media, also building material. A comparison with data from literature determined on building materials are shown for the LIM`s of substrate class I (biodegradable materials) and substrate class II (porous materials) in Figure 3. The resulting LIM for substrate I is below the data given by (Clarke et al. 1999, Hens 1999, Viitanen 1996, Viitanen et al. 2000), while the LIM for substrate II builds up the upper limit.

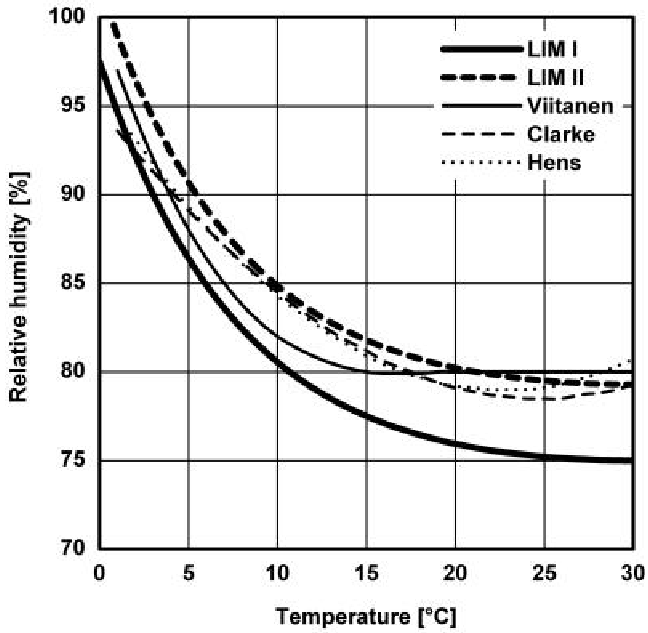


Figure 3. Comparison of the LIM`s of substrate class I (biodegradable materials) and substrate class II (porous materials) with data from literature determined on building materials. The resulting LIM for substrate I is below the data given by the authors mentioned above, while the LIM for substrate II builds up the upper limit.

4 APPLICATION OF THE ISOPLETH SYSTEM

Mould growth damages are not rare in non-insulated houses (Künzel 1999). But mould growth can also occur in insulated houses, insulated according to today's standards, when too high humidity (for example due to build-in moisture) are combined with insufficient ventilation. Calculations with a new hygrothermal building simulation tool, which has been developed at the IBP and which is being validated, show in which way increasing air humidity appears because of build-in moisture in the first years after construction (Sedlbauer 2001). With it a wall construction (made of aerated concrete) with an assumpted U-value in its standard cross-section of 0.25 W/m^2K. As build-in moisture an initial water content of 20 Vol.-% is taken in account for the calculation. The change of air rate has been decreased to an extremely low value of 0.1 h^{-1} starting with the DIN-Standard required 0.5 h^{-1}, which should be realistic based on closed windows in some cases. The results of these calculations – hour values of the temperature and the relative humidity in a living room – have served as boundary condition for the following determinations of the boundary conditions on the surface of the wall. This way the hygrothermical situation has been examined on the external wall in the corner, behind a closet as well as in the extreme case in the corner behind a closet. The internal heat-transfer coefficient is assumed for the unobstructed wall corner with 5 W/m^2K, behind the closet on the external wall a value of 4 W/m^2K and in the corner a value of 2 W/m^2K is assumed. With the calculations it is assumed that the house will be lived in after one month after building finish. The calculations take place for the first heating period.

Figure 4 shows the internal relative humidity calculated with the hygrothermal building simulation tool for a decreased air change of 0.2 h^{-1} with concomitance of built-in moisture

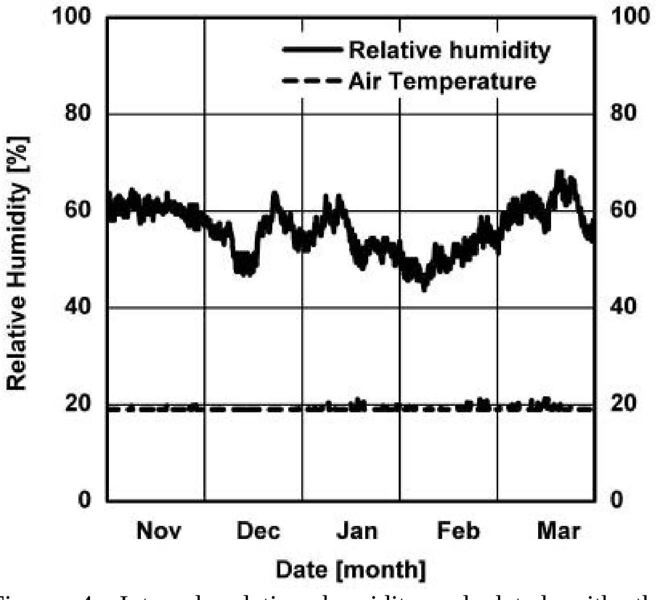


Figure 4. Internal relative humidity calculated with the hygrothermal building simulation tool for a decreased air change of 0.2 h-1 with concomitance of built-in moisture.

The calculated temperatures and relative humidities on these different spots on the wall serve as boundary conditions for the judgement of a possible mould growth with the isopleth system. These transient courses of temperature and relative humidity on the component surface as growth conditions are compared with the data in the corresponding isopleth systems of the spores germination time respectively the mould growth. These data can for example be plotted as hourly values in the isopleth systems. With help of the individual isolines (for example four days) it is fixed, which contribution an hourly value, which lies for example on this isoline, leads to spore germination (in this case it is one hour/4 (days) x 24 hours) = 0.01). These values are added and shown as a germination course dependent on time. When the total value reaches 1, it is assumed, that the spore germination is finalised and that the fungus is starting to grow. This results in an easy way of assessment; it can be shown, whether it comes to spore germination in a specific time. Analogue to this with help of the substrate specific isopleth system for mould growth the celerity of mycelium grows can be determined.

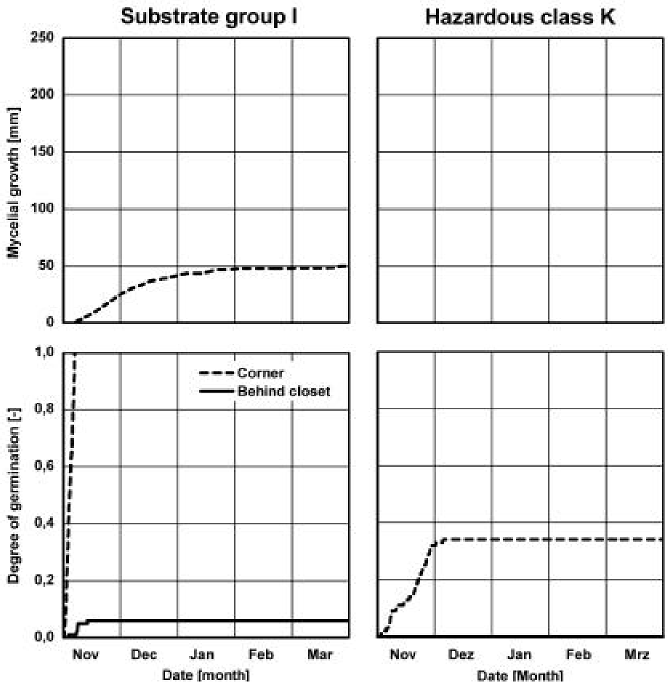


Figure 5. Course of the calculated degree of germination (below) and mycelial growth (above) for a decreased air change of 0.2 h-1 with concomitance of built-in moisture underlying the isopleths of substrate group I (left) and hazardous class K (right).

Figure 5 left shows the results of substrate group I determined by the described way. Despite of build-in moisture mould growth is not prognosed by air change of 0.5 h^{-1} or by a decreased air change of 0.3 h^{-1} (both cases not shown). But when the air change rate is decreased to 0.2 h^{-1}, it rapidly comes to complete germination in the corner. In the free wall corner only a small mould growth appears, it is to be expected that in the corner behind the closet a clear growth appears.

Because the isopleth system for fungi estimated as critical, although determined for ideal medium, mean higher growth demands, other results are obtained (see Fig. 5 right). They show, that these fungi do not grow in contrast with the other ones under these conditions.

5 BIOHYGROTHERMAL MODEL

For transient boundary conditions of temperature and relative humidity, either spore germination time or the myzel growth can be determined with the help of these Isopleth systems. The assessment of spore germination on the basis of the Isopleth model has the disadvantage that an interim drying out of the fungi spores cannot be taken into account in case of occurring transient micro-climatic boundary conditions. Therefore in these cases, this process will more often predict the germination of spores than the following Biohygrothermal model. In order to describe the mode of action for the fundamental means of influence on the germination of spores, i.e. the humidity available at certain temperatures, this new model was developed.

The decisive condition for the germination of the spores is the ambient humidity which determines the moisture content within a spore. The objective of the so called “Biohygrothermal Model“ (Sedlbauer 2001) is to predict this moisture balance as affected by realistic unsteady boundary conditions as found in buildings, in order to permit predictions of growth probabilities. Of course, the moisture content of a spore is also determined by biological processes, but the current knowledge is far from sufficient to allow modelling of these. It is safe to assume that only above a certain minimum moisture content the spore begins to germinate and no biological metabolic processes occur before that. Until then, the spore may be considered as an abiotic material whose properties are subject to purely physical principles (see Fig. 6). The Biohygrothermal Model only describes the development of the spore up to this point. Due to the small size of the spore an isothermal model is sufficient, so that liquid transport processes (such as capillary suction) can be lumped together with diffusion transport. Under these assumptions only the moisture storage function of the spore and the moisture-dependent vapour diffusion resistance of the spore wall are needed as material parameters in order to enable the calculation of the moisture balance of a spore. According to the assumptions noted earlier the germination of spores is principally affected by thermal and hygric conditions only. Therefore it should be independent of the substrate. But normally the starting point of germination is defined by the first visible growth and not by the start of metabolism. The apparent start of germination depends on the quality of the substrate according to these considerations. This influence of the substrate is taken into account by using the LIMs (Fig. 1) in order to calculate the so called critical water content. The Biohygrothermal model is implemented in WUFI (Künzel 1994), a program for the calculation of non-steady heat and moisture transfer. This calculation program is spread over Europe and successfully validated by numerous authors

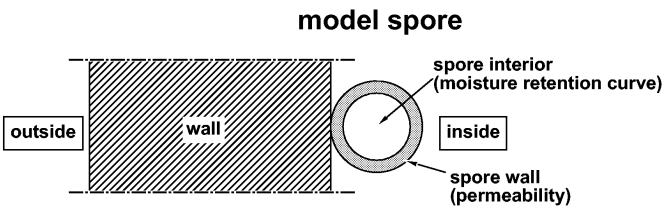


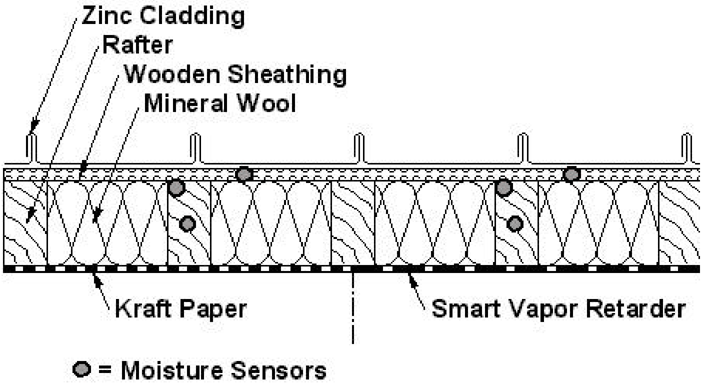
Figure 6. Schematic diagram of the Biohygrothermal Model (Sedlbauer 2001).

6 EXAMPLE “ROOF COVERED WITH METAL SHEETS“

Roofs covered with metal sheets have a very high vapour diffusion resistance, so that virtually no moisture can escape through the covering. Therefore, a sufficiently permeable inside vapour retarder must allow the moisture to dry out towards the room side, especially during the warm summer months. In order to compare different vapour retarders, extensive investigations were carried out in the outdoor-testing field of the Fraunhofer Institute for Building Physics (IBP).

Because of the high insolation on the southern plane of the roof and the resulting high temperatures of the metal covering, so-called summer condensation occurs. This means that moisture diffuses from the hot outer parts of the roof assembly to the cooler room side and temporarily increases the humidity at the vapour retarder. The above mentioned outdoor tests show that a polyamide sheet results in the lowest wood moisture levels so that the proper function of this kind of vapour retarder could be confirmed. In the variant conducted with kraft paper, mouldy odour and patches of mould were found at the end of the investigations which showed that extensive mould growth had taken place in the roof assembly.

This gable roof has a pitch of 50° and the ridge is oriented in an east-west direction, so that one of the roof planes is facing north and the other is facing south. Figure 7 (top) displays the basic design of the test sections. The interior view of the insulated roof in Figure 7 (bottom) shows the three different variants. The space between the rafters (rafter height 18 cm) had been completely filled with mineral wool (thermal conductivity ca. 0.04 W/mK), so that no air gap was left between the insulation and the rough boarding (30 mm thick). For rafters and boarding moist wood with a moisture content of at least 30 mass-% had been used. The investigated vapour retarders were Kraft paper with a permeability of approx. 3 m, a polyethylene sheet with 50 m and a smart vapour retarder (Künzel 1999) with a permeability between 0.4 and 4 m, depending on the ambient humidity.



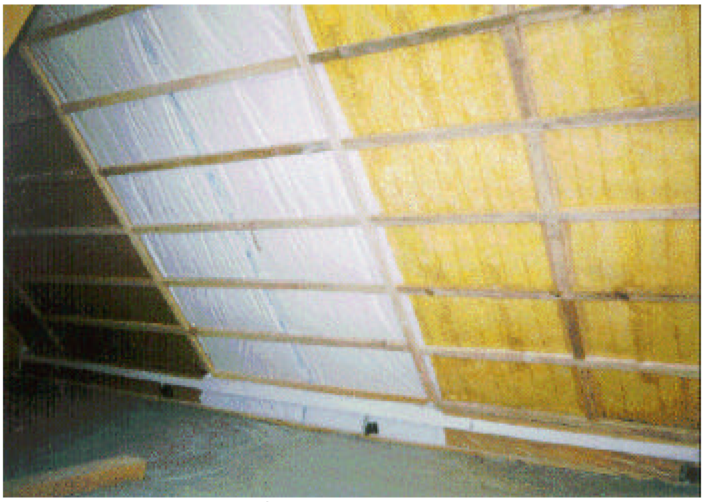
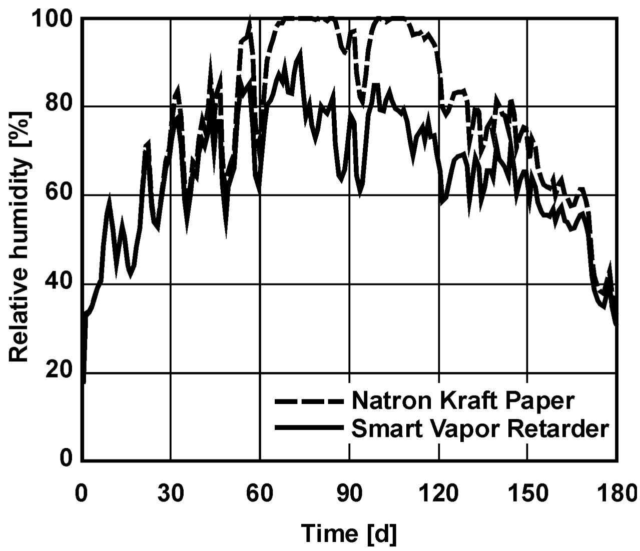


Figure 7. The tested roof covered with metal sheets.
Top: Basic design of the test sections.
Bottom: Photographical view of the interior.

The variation of RH on the inner surfaces of the Kraft paper and the smart vapour retarder in this roof, calculated with the aid of the WUFI model for an observed period of 180 days, are shown in Figure 8 (top). The surface temperatures (not shown in Fig. 8) were nearly constant with time at about 21 °C. These records have served as boundary conditions for the calculation of the courses of the water content inside the spore in step 2 of the analysis. Due to the high vapour diffusion resistance of the spore wall the courses of the calculated moisture content in the spores are smoothened (compare Fig. 8 (bottom)) compared to the RH on the inner surface of the roof. On Kraft paper the spore shows a distinctive higher water content in comparison with the smart vapour retarder and reaches more than 60 % per Volume. Additionally the variation of the starting point of germination are implied for both materials. Since the surface temperature was nearly constant these records show almost no change with time. It is evident, that the water content of the spore calculated for the Kraft paper lies for a long period at a much higher level than necessary for germination. After about 30 days the growth of mould starts, a result which is quite consistent with the observations on this roof. With the polyamide foil the moisture content exceeds this limit only for a very short period and therefore no risk of mould growth should be expected.



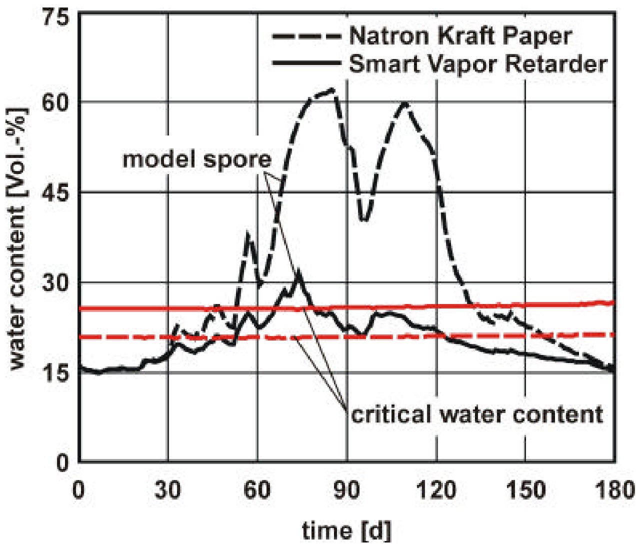


Figure 8. Calculated results for the vapour retarders inside the roof (Sedlbauer 2001).

Top: Courses of the relative humidities on Kraft paper and smart vapour retarder. This courses serves as boundary conditions for the calculation of the moisture balance of the spore.

Bottom: Courses of the water content inside the spores on Kraft paper and smart vapour retarder. The courses of the starting point for germination are implied for both materials (horizontal lines).

Figure 9 shows the results for the hazardous class K. For the smart vapour retarder the occurrence of these Hazardous mould fungi can be excluded. For Kraft paper instead the risk to get them is obvious.

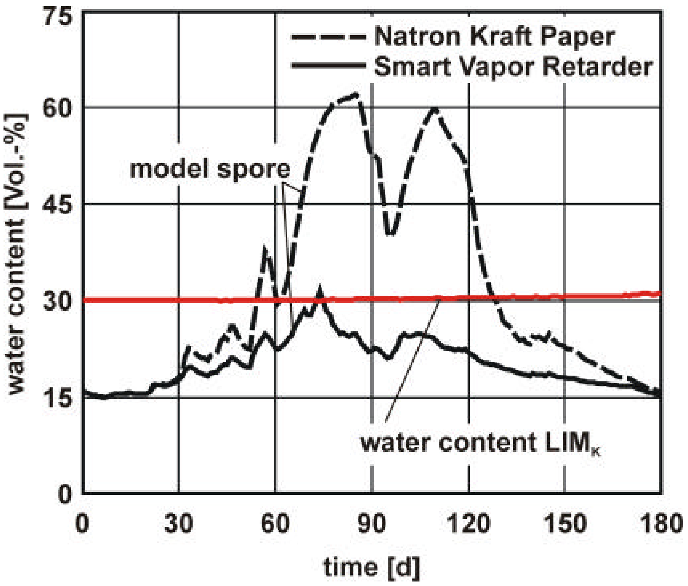


Figure 9. Calculated results for the vapour retarders inside the roof (Sedlbauer 2001). Courses of the water content inside the spores on Kraft paper and smart vapour retarder. The courses of the starting point for germination of mould concerning to the hazardous class K is implied (horizontal line).

7 SUMMARY

The only chance for the long term prevention of mould growth is to ensure that the hygrothermal situation on the surface is not convenient for mould growth. The use of biocides works only for a limited period and may affect health and environment. Up to now the common methods to assess the risk of mould growth are based on steady boundary conditions. While in Germany only relative humidity is stated as a decisive condition for mould growth, more and more measured Isopleths are used abroad. These isopleths state, depending on temperature, the relative humidity from which mould growth may occur. But all curves for growth are determined with steady state conditions, in spite of the non-steady state conditions in reality. This newly developed model, describing the hygrothermal behaviour of the spore, allows for the first time to account for the changing surface temperatures and RH's for the prediction of mould growth. The capability of the Biohygrothermal Model to assess the risk of mould growth has been demonstrated impressively with the chosen example. This model allows a fast, easy and reliable judge of an existing or planned construction or of a refurbishment measure concerning mould growth.

8 REFERENCES

Adan, O. 1994. *On the fungal defacement of interior finishes.* (Thesis). Eindhoven: University of Technology.

Ayerst, G. 1969. The effect of moisture and temperature on growth and spore germination in some fungi. *Journal of Stored Products Research,* H. 5: pp. 127 - 141.

Block, S.S. 1953. Humidity requirements for mold growth. *Applied Microbiology 1,* H. 6: pp. 287 - 293.

Clarke, J. A. et al. 1999. A technique for the prediction of the conditions leading to mould growth in buildings. *Building and Environment Nr. 34*: pp. 515 - 521.

Deutsches Institut für Normung 1999. *Wärmeschutz und Energie Einsparung in Gebäuden, Teil x: Vermeidung von Schimmelpilzen (heat protection and energy saving in buildings, part x: prevention of mould growth).* Beuth Verlag, draft from 10.05.99.

Grant, C. et al. 1989. The moisture requirements of moulds isolated from domestic dwellings. *International Biodeterioration 25*, pp. 259 - 284.

Hens, H.L.S.C. 1999. Fungal defacement in buildings: A performance related approach. *International Journal of Heating, Ventilation, Air-Conditioning and Refrigerating Research*, Vol. 5, H. 3, pp. 256 - 280.

Krus, M. & Sedlbauer, K. 2002. Brauchen wir Gefährdungsklassen für Schimmelpilze zur Beurteilung von Baukonstruktionen? (Do we need hazardous classes of mould fungi for the assessment of building parts?), *Tagungsbeitrag für das 11. Bauklimatische Symposium der TU Dresden. 26. – 30. Sep. 2002,* Dresden, pp. 790 – 802.

Künzel, H. M. 1999. Flexible vapour control solves moisture problems of building assemblies – Smart Retarder to replace the conventional PE-film. *Journal of Thermal Envelope & Building Science*, Vol. 23, pp. 95-102.

Sedlbauer, K. 2001. *Vorhersage von Schimmelpilzbildung auf und in Bauteilen* (Predictuion of mould manifestation on and in building parts). (Thesis). Stuttgart: University of Stuttgart.

Viitanen, H. 1996. *Factors affecting the development of mould and brown root decay in wooden material and wooden structures.* (Thesis). Uppsala.

Viitanen, H. et al. 2000. Modelling mould growth and decay damages. *Proceedings of Healthy Buildings*, Vol. 3, pp. 341 – 346.