Biohygrothermal method for the prediction of mould growth: procedure and health aspects

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ABSTRACT
In buildings growing conditions for mould fungi can occur and cause fungus infestation. The possible 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 result from mould fungi 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 boundary conditions for the growth of fungi are temperature, humidity and substrate conditions which have to be simultaneously favourable over a certain period of time. In the Fraunhofer-Institute of Building Physics (IBP) in Germany a biohygrothermal procedure is developed, which allows the prediction of mould growth under transient boundary conditions. In order to differentiate the mould fungi according to the health dangers they may cause, so-called hazardous classes were defined. This new method will be described with its new features and its limitations. Typical results of this model are shown within an example. Furthermore the significance of the results is discussed.

INDEX TERMS
Mould; Health effects; Modelling

INTRODUCTION
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 humidity (Grant, 1989) and temperature (Smith, 1982) as well as the substrate (Ritschkoff, 2000) have to be available over a certain period of time 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.

HEALTH ASPECTS OF MOULD
People are exposed to mould spores in the air they breathe daily; however, sometimes moulds grow excessively in certain areas and can cause different types of illnesses (Pasanen, 2001). The most prevalent affect of mould on human health is caused by the allergenic impact of its spores (Horner, 1995). Some moulds are more hazardous than others. Different people have different responses to mould exposure. In particular, those with allergies, existing respiratory conditions or suppressed immune systems are especially susceptible to health problems. In addition, some moulds produce chemicals called mycotoxins, which can cause flu-like

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symptoms. It should be noted that the causes and effects of mould exposure on people are not very well understood. For this reason mould growth should be restricted as far as possible.

GROWTH CONDITIONS FOR MOULD

German literature often states a relative humidity of 80% at wall surfaces as decisive criterion for mould growth, independent of temperature. Sometimes it is mentioned that many types of mould can also thrive at lower humidities (see, e.g. 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 (Ayerst, 1969). These diagrams describe the germination times or growth rates. Beyond the lowest line every mould activity ceases, under these unfavourable 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. It is assumed that germinable spores are present in most cases. This means that mould growth will occur when hygrothermal growth conditions are fulfilled.

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. 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 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 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 substrates were suggested that could be derived from experimental examinations:

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 nutrients.

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 (Figure 1, left). Persistent building materials with high open porosity mostly belong to substrate category II. 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.

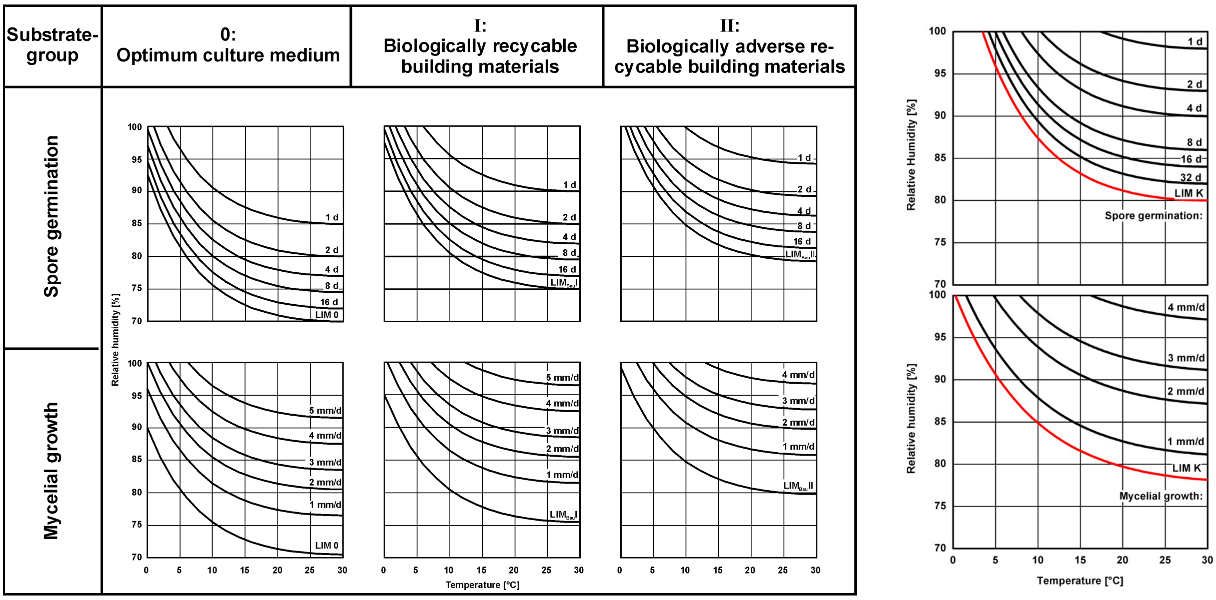

Figure 1 Isopleth systems for three categories of substrates (left), in order to regard the influence of the substrate on the formation of mould fungus (Sedlbauer, 2001) and Isopleth systems for the so-called critical fungus species (right).

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 and Sedlbauer, 2002): The isopleth system K applies to mould fungi, which are discussed in the literature because of their possible health effect (Figure 1, right). For these species (*Aspergillus fumigatus*, *Apergillus flavus* and *Stachybotrys chartarum*) growth data from Sedlbauer (2001) are available. The isopleth system for the fungi estimated as critical is based on the available data on optimum culture medium. To make an adequate substrate specific isopleth precise measurements are missing. To move the isopleth to a higher humidity analogically to the development of the imagined building material isopleth, is too risky especially for these fungi according to today's knowledge.

APPLICATION OF THE ISOPLETH SYSTEM

Mould growth damage is 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 (e.g. due to built-in moisture) is 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 built-in moisture in the first years after construction (Sedlbauer, 2001). With it a wall construction (made of aerated concrete) with a U-value in its standard cross-section of 0.25 W/(m^{2}K) has been investigated. As built-in moisture an initial water content of 20 Vol.% is taken in account. 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 temperature and relative humidity—have served as boundary conditions for the following determinations of the boundary conditions on the surface of the wall. This way the hygrothermal 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^{2}K), behind the closet on the external wall a value of 4 W/(m^{2}K) and in the corner a value of 2 W/(m^{2}K) is assumed. With the calculations it is assumed that the house will be lived-in after 1 month after completion. The calculations take place for the first heating period.

The calculated 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. These data can, for example, be plotted as hourly values in the isopleth systems. With help of the individual isolines (e.g. 4 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 1 h/4 (days) × 24 h) = 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 finalized 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 2 (left) shows the results of substrate group I determined by the described way. Despite of built-in moisture mould growth is not prognosed by an 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) other results are obtained (see Figure 2, right). They show, that critical fungi do not grow in contrast with the other ones under these conditions.

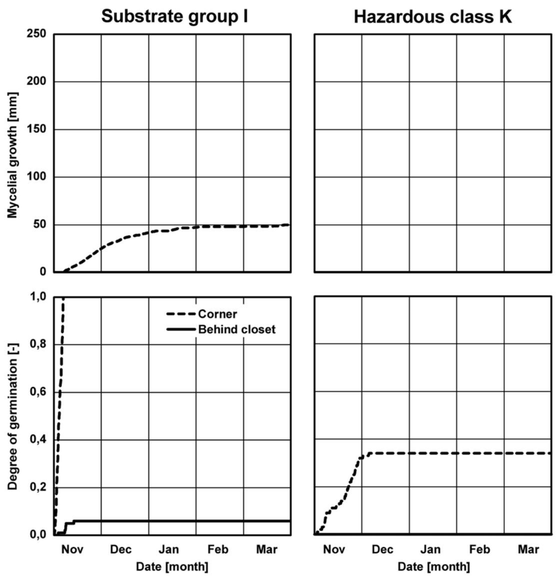

Figure 2 Course of the calculated degree of germination (below) and mycelial growth (above) for a decreased air change of 0.2 h^{-1} with concomitance of built-in moisture underlying the isopleths of substrate group I (left) and hazardous class K (right).

BIOHYGROTHERMAL MODEL

For transient boundary conditions of temperature and relative humidity, either spore germination time or the mycel 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 Figure 3). 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 (Krus, 1996). According to the assumptions noted earlier the germination 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 (Figure 1) in order to calculate the so-called critical water content.

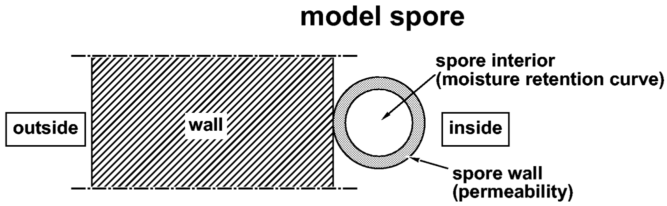

Figure 3 Schematic diagram of the biohygrothermal model (Sedlbauer, 2001).

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 test site of the 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 4 (left) displays the basic design of the test sections. The interior view of the insulated roof in Figure 4 (right) shows 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.

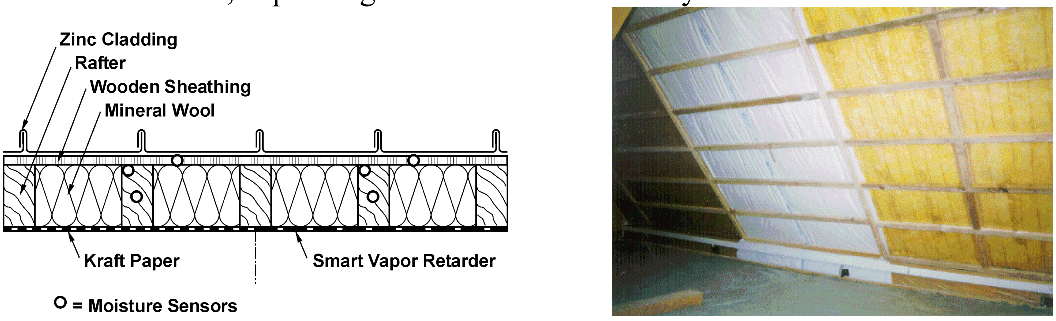

Figure 4 The tested roof covered with metal sheets. Left: basic design of the test sections; Right: photographical view of the interior.

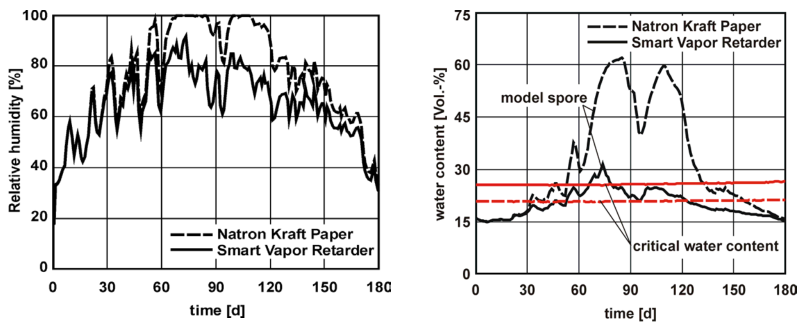

Figure 5 Calculated results for the vapour retarders inside the roof (Sedlbauer, 2001). Left: Courses of the relative humidities. This courses serves as boundary conditions for the calculation of the moisture balance of the spore. Middle: Courses of the water content inside the spores. The courses of the starting point for germination are implied for both materials (horizontal lines). Right: Courses of the water content inside the spores. The courses of the starting point for germination of mould concerning to the hazardous class K is implied.

The variation of RH on the interior 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 5 (left). The surface temperatures (not shown in Figure 5) 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 Figure 5 middle) compared to the RH on the interior surface of the roof. On Kraft paper the spore shows a distinctively 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 is 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. The right side of Figure 5 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.

SUMMARY

This newly developed model, describing the hygrothermal behaviour of the spore, allows for the first time to employ the changing surface temperatures and RH's for the prediction of mould growth. The calculational assessment of mould growth allows the handling of problems which until now couldn't be solved with simple estimations or with reasonable metrological expense. Therewith the effectivity of refurbishment measures on behalf of the elimination of the risk of mould growth can be determined. The optimization of building constructions may now be performed in an easy way. The biohygrothermal model additionally is of great use for detemining the necessary rate of ventilation. The use of the hazardous class K enables to asses the actual call for action.

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