Comparative Evaluation of the Predictions of Two Established Mold Growth Models

Martin Krus, DrIng **Michael Seidler** **Klaus Sedlbauer, DrIng**

ABSTRACT

Although the energy codes and standards for buildings have been considerably improved in the last decades, there are consistent reports on building damage caused by mold growth. Numerical models for predicting mold growth can be useful in assessing the risk of mold growth in new construction and retrofit applications. Two well-known models exist and are widely used: the Viitanen (VTT) model and the biohygrothermal model. While the VTT model is an empirical model, the biohygrothermal method is based on a theoretical model and considers transient ambient conditions. The result is mold growth in millimeters, which is, however, not intelligible to all. The Scandinavian countries in particular established a very clear six-step evaluation model, the so-called mold index. *By combining the results of the biohygrothermal model and the mold index of the VTT model, it is possible to use a clear and acknowledged rating measure. A conversion function was developed allowing the transformation of the calculated growth, in millimeters, into the mold index with a high level of correspondence.*

INTRODUCTION

Numerous damage cases in residential and nonresidential buildings can be directly or indirectly attributed to the impact of moisture. Besides reducing potential damage risks, the renovation of existing buildings should be aimed at improving the energy performance. This may result in the reduction of already existing problems with moisture—e.g., mold growth on internal surfaces caused by temperatures that are too low—but will probably also generate new moisture problems. Therefore, mold growth, particularly on internal surfaces of external building envelope components but also in other areas on or inside building assemblies, has become an essential point of discussion in recent times. To remove or avoid mold growth creates considerable costs. Mold growth may pose a health risk for residents (Mücke and Lemmen 1999). In the case of mold damage, the question is whether the building design and construction were the cause or whether the cause is incorrect occupant behavior in the sense of insufficient ventilation or excessively high humidity levels. To clarify the answer, measurements as well as modern hygrothermal calculation methods are applied to provide information on the existing transient moisture conditions and to assess the risk of mold growth.

The biohygrothermal model described by Sedlbauer (2001) is an established calculation method for predicting the risk of mold growth on internal surfaces with transient boundary conditions. It is based on measured mold growth isopleths and on the calculation of the transient water content of a model spore. The result is growth in millimeters, which is, however, not intelligible to all. The in the Scandinavian countries, a six-step assessment model has been established in the meantime, the so-called *mold index*, introduced by Viitanen and Ritschkoff (1991) and based on the percentage of the area surface covered by mold. Since the mold index is more generally understandable, the aim of this work is to compare the results of both models and to convert the results from the biohygrothermal model into Viitanen's mold index.

Martin Krus *is deputy head of the Department of Indoor Environment, Climatic Impacts, Fraunhofer Institute for Building Physics, Valley, Germany.* ***Michael Seidler*** *is head of the Michael Seidler Bldg Co., Dortmund, Germany.* ***Klaus Sedlbauer*** *is a full professor in the Department of Building Physics of Faculty 2, Department of Civil and Environmental Engineering, University of Stuttgart, Stuttgart, Germany.*

DESCRIPTIONS OF THE TWO MODELS

Biohygrothermal Model: WUFI®-Bio

The assessment of the risk of mold growth on building surfaces and internal building components is of special importance for building practice. Since temperature and moisture conditions are essential influencing factors of mold growth, knowledge of transient hygrothermal conditions may provide information on spore germination and mycelium growth of mold fungi. Isopleth systems describe the dependence of spore germination or mycelium growth on the surface temperature and humidity. Isopleth systems (Lowes isopleth for mold [LIM] limiting curve) for four groups of substrates that could be derived from experimental examinations were suggested. They are:

Substrate group 0:	optimal culture medium
Substrate group I:	biodegradable building materials
Substrate group II:	building materials containing some biodegradable compounds
Substrate group III:	nonbiodegradable building materials without nutrients

Figure 1 shows for these substrate groups the generalized isopleth systems for spore germination and for mycelium growth valid for all relevant species of mold fungus occurring in construction. For substrate group III, no isopleth system is given since it is assumed that formation of mold fungi is not possible without soiling of the surface. In case of considerable soiling, substrate group I always has to be assumed. Building materials with high open porosity, such as brick or stucco, mostly belong to substrate group II.

In all available isopleth systems, the mycelial growth is given in millimeters per day (mm/d), which is therefore chosen as the unit used in the biohygrothermal model. For the beginning of the growth this may be a reasonable unit, describing the increase of the length of on mycel. But with ongoing growth you get a meshwork of mycels differing in area and thickness. The calculated mycelial growth, which can reach values of several hundred millimeters, is valuable for the comparative assessment of the risk of mold growth but it isn't really imaginable.

Sedlbauer (2001) developed a biohygrothermal model 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 in a correct way from the physical point of view. This model allows the calculation of the moisture content in a spore in dependence of transient boundary conditions, i.e., it is also possible to consider intermediate drying of the fungus spores. Figure 2 shows a schematic view of the model spore on the wall, which is the basis of the biohygrothermal model.

If the specific water content (critical water content) is achieved inside the spore, germination can be regarded as completed and mold growth will begin. This critical water content is derived from the LIM curves of the isopleth systems

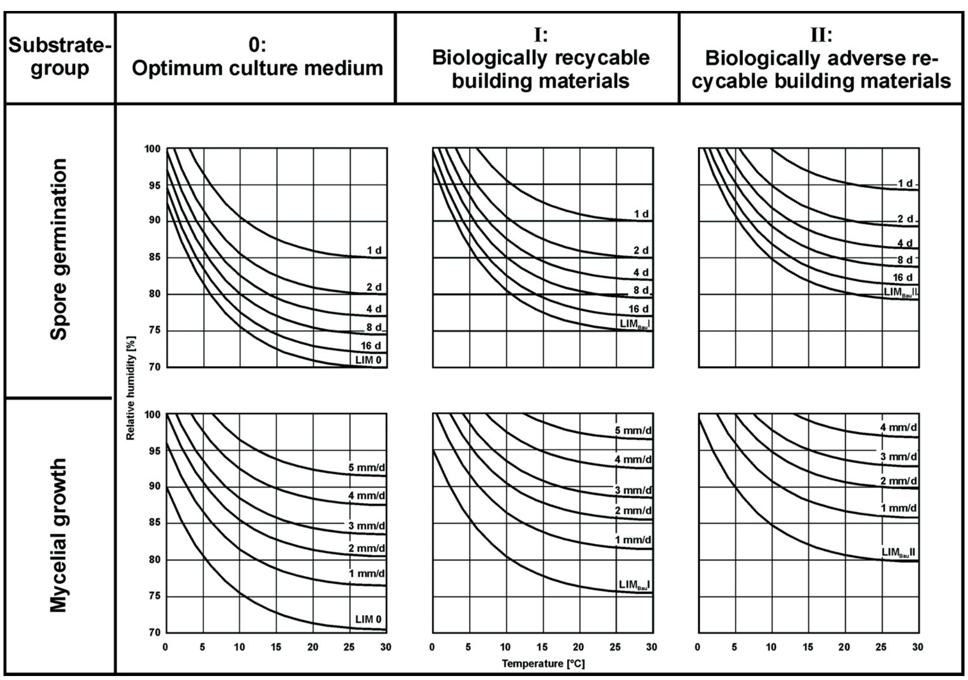

Figure 1 *Generalized isopleth systems (Sedlbauer 2001) for spore germination (top) or mycelium growth (bottom) valid for all kinds of mold fungi occurring. The diagrams present on the left the optimal substrate, in the centre substrate group I, and on the right substrate group II.*

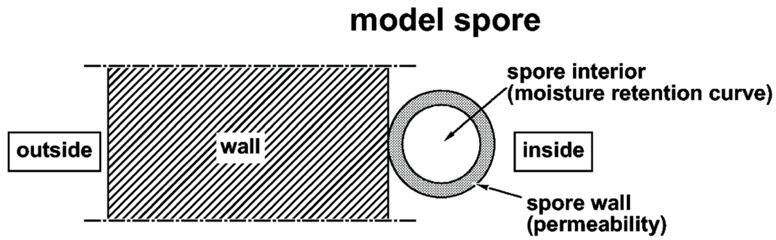

Figure 2 *Schematic view of the model spore on the wall (Sedlbauer 2001). The spore is approximately 1:100.000 in scale.*

for spore germination. This critical water content is strongly dependant on temperature and the moisture retention curve of the model spore. Therefore, the input data of this biohygrothermal model is the temperature and relative humidity on the surface, which may be a result of measurements or of hygrothermal calculations, and the substrate group to which the material belongs. Further detailed information on this model and examples of its application can be found in Sedlbauer and Krus (2003). Figure 3 presents characteristic results of this program.

The Model of Viitanen (the VTT Model)

The fundamentals of the VTT mold growth model were developed by Viitanen and Ritschkoff (1991) under laboratory conditions. The objective of this work was the determination of the times for germination and the mold growth on pine and spruce wood as well as their deterioration under defined humidities and temperatures to get the essential data for modeling. Based on numerous laboratory experiments with various constant temperature and humidity conditions, the mathematical modeling was developed. Related studies were performed in the laboratory, since the interaction of surface humidity, material moisture content, temperature, time, and microbial growth in buildings was difficult to simulate and analyze. In the model, constant and periodically changing climate conditions, as well as the type of wood and the surface qualities, can be selected as boundary conditions. These models have undergone continuous development, including the decrease of mold growth due to fluctuating moisture conditions as well as mold growth on mineral-based materials (see, e.g., Viitanen and Ojanen [2007] and Viitanen [2005–2009]). The results are presented in the mold index described in the following section.

Mold Index (Wood-Based Material)

0 = no growth
1 = some growth (microscopy)
2 = moderate growth (microscopy), coverage > 10%
3 = some visually detected growth (thin hyphae found under microscopy)
4 = visual coverage > 10% (growth found under microscopy)
5 = coverage > 50%
6 = dense coverage 100%

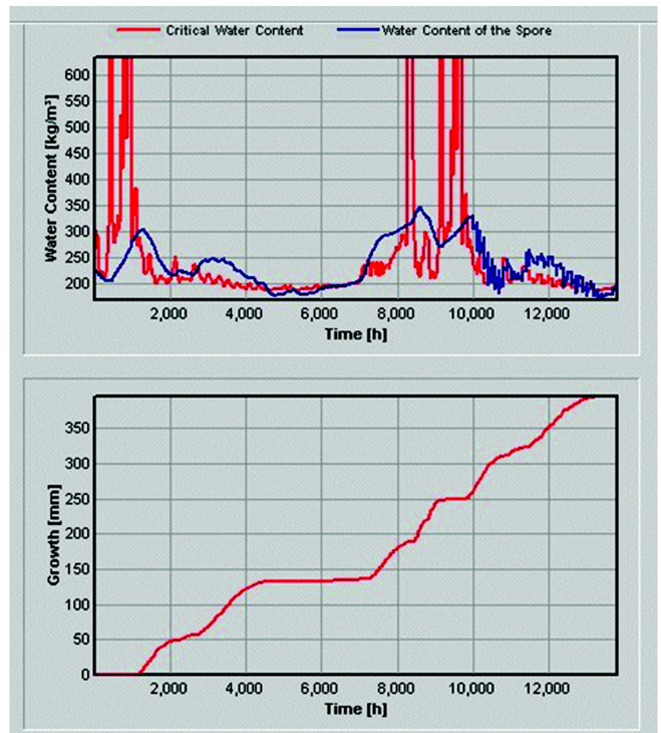

Figure 3 *Results of a calculation by means of the current biohygrothermal model.*

The results for mineral materials are presented according to Viitanen (2005–2009) in the latest VTT model with a separate definition of the mold index. Thus, the same mold index means quite a different growth according to the respective substrate materials.

Mold Index (Stone-Based Material)

0 = no growth
1 = some growth
2 = moderate growth (coverage > 10%)
3 = coverage > 50%
4 = coverage > 50% but < 100%
5 = coverage 100%

A different intensity in growth with the same mold index (according to the respective selection of the substrate) is hardly practice-oriented or clear. Therefore, the development of a transfer function is exclusively based on the mold index defined by Viitanen for wood-based materials.

Basic Differences of the Two Models

The two models, the biohygrothermal model and the VTT model, are quite different. The VTT model is an empirical model exclusively based on laboratory investigations. In contrast, the transient biohygrothermal model is a theoretical model. The biohygrothermal model allows selection between various substrate groups that can also be extended by specific measured material substrate groups. The Viitanen model only allows the differentiation between two different wood types or a mineral-based substrate.

Growth calculated under conditions unfavorable for mold growth can be retrogressive in the Viitanen model, in contrast to the biohygrothermal model, which shows zero growth at these times. Even at temperatures below 0°C, the biohygrothermal model shows a slight growth in contrast to the Viitanen model. The most essential difference, however, is that the Viitanen model does not allow any increase of predicted mold growth beyond a limit value that is dependent on the respective climate boundary conditions, whereas the biohygrothermal model allows continuous growth as long as there are suitable boundary conditions.

TRANSFORMATION OF CALCULATED GROWTH INTO THE MOLD INDEX

The development of the VTT model was based on various laboratory experiments. Unfortunately for these experiments, the boundary conditions were not documented in a way applicable for the biohygrothermal model. Therefore, the transfer was based on numerous hygrothermal calculations to derive the surface conditions for both models. The advantage of this method was that real and transient boundary conditions, which occur on the internal surfaces, may serve as a basis, allowing a variety of parameter variations. The hygrothermal calculations were carried out using the one-dimensional hygrothermal simulation tool, WUFI®, which was developed at the Fraunhofer-Institut für Bauphysik (IBP). The simulation tool has been validated in many applications (see Künzel et al. [1995], Hens et al. [1996], Krus et al. [1999], and Künzel et al. [2002]). The resulting surface conditions served as the input parameters for the biohygrothermal model as well as for the VTT model, which was made available for these investigations.

Parameter Variations

The parameters chosen for investigation were location (exterior climate), construction type, indoor climate, and thus the moisture load. With respect to the selection of location, special emphasis was placed on investigating a wide range of climates. Besides locations with very cold winters, in Northern Europe, North America, and the Alps, for example, other locations with high driving rain loads on the North and Baltic Seas were selected. Locations with continental climates in Eastern Europe and moderate climates in Central Europe as well as Mediterranean climates, in Italy and Spain for example, were taken into consideration. A total number of 32 different locations were investigated.

Indoor climate conditions were derived from the outdoor climate conditions according to EN 15026 (CEN 2007) or ASHRAE Standard 160 (ASHRAE 2009). The inhabitant's behavior was varied, resulting in increased internal moisture loads. With regard to indoor temperatures, numerous variations from 19°C ± 3°C to 24°C ± 2°C were calculated. This variety of 14 indoor climates was intended to simulate as many user behaviors as possible. In fact, microbial growth primarily occurs due to occupant behavior—specifically that regarding heating and ventilation or obstruction of free convection of indoor air to external wall surfaces by furniture or curtains.

U-factors from 0.3 to 1.9 W/(m^2·K) were used for the selected external wall assemblies. External walls with poor insulation standards were given a high degree of consideration, as they are especially susceptible to microbial growth. The extremely high U-factors were intended to simulate the surface areas of thermal bridges. Monolithic constructions made of various materials, such as brick and aerated concrete, as well as lightweight constructions were investigated.

Development of the Transformation Function

Approximately 350 calculations were performed; these serve as a basis to develop the transformation function. The evaluation of results was performed by comparing the respective maximum values (mold index and growth in millimeters) during the simulation period, 365 days. Calculations were started at the beginning and in the middle of the year. A particular point in time for the evaluation was deliberately avoided, since both methods show different intensities of mold growth under particular climate boundary conditions and at different times. Figure 4 shows the results of the VTT and biohygrothermal models for all cases. The red line represents a polynomial regression fit to the data.

This transfer function already presents an acceptable result. However, there is a large scope of variations within the range of mold index 6. Some overestimations but almost no underestimations occur at a lower mold index. These deviations occur due to the specific differences of the models. Whereas the VTT model shows a maximum value (mold index 6), extremely high values under favorable growth conditions can be generated by the biohygrothermal model. Overestimation by the biohygrothermal model occurs at lower mold indices when mold growth is reduced during periods of unfavorable boundary conditions by the Viitanen model. A reduction in growth cannot occur in case of the current biohygrothermal model.

Consequently, two modifications were carried out. If mold index 6 is reached in the Viitanen model at a certain time, the calculation will only be carried out up to this point of time in the biohygrothermal model. Moreover, in all variations where reductions in growth occur according to the VTT

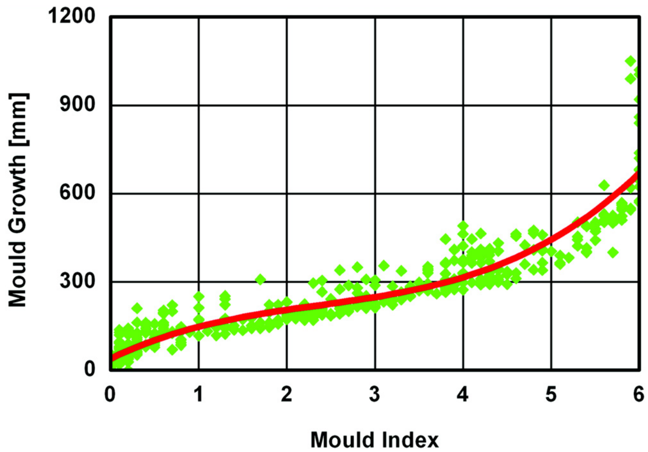

Figure 4 *Comparison of the results calculated by both models for the different variations over a period of one year. The red line in the diagram is a polynomial fit of the data.*

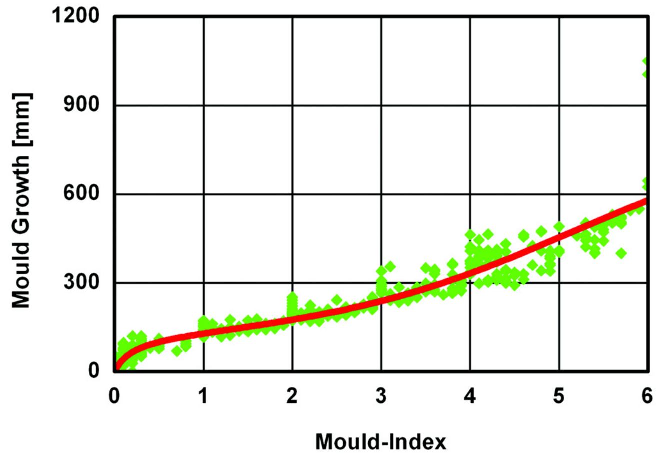

Figure 5 *Comparison of the results calculated using both models. The red line in the diagram represents a fitted BET function.*

model, the results were corrected by the sum of reductions. The new results of both models are shown in Figure 5. An even better correlation in the lower range resulted. Because of the shape of the dependency between mold growth and mold index, which looks like a typical sorption isotherm, a BET adsorption curve (see Brunauer et al. [1938]) serves as a regression curve. The function, given as a red line, corresponds well with the results over the total range and thus represents an appropriate transfer function.

SUMMARY

Microbial growth may pose a health risk for residents. The application of biocides can prevent mold growth for only a limited period of time in most cases. Therefore, mold growth on the surfaces of building components should be avoided by well-founded measures. In this context, a preventive strategy should be applied that prevents boundary conditions favorable for mold growth from occurring. Such strategies can be devised by investigating the transient hygrothermal processes in buildings using hygrothermal simulation tools.

Calculation models to predict mold growth can provide essential information on how to avoid mold growth and assess the risk of mold growth of proposed renovation measures. There are primarily two models that are well known and widely used in practice: the VTT model and the biohygrothermal model. While the VTT model is an empirical model exclusively based on laboratory investigations, the biohygrothermal method is a theoretical model and considers transient ambient conditions. The result is mold growth in millimeters, which is, however, not intelligible to all. The Scandinavian countries in particular established a very clear six-step evaluation model in the meantime, the so-called *mold index*, which is implemented in the VTT model, based on coverage by percentage.

By combining the results of the biohygrothermal model and the mold index of the Viitanen model, it is possible to use a clear and acknowledged rating measure. A transformation function was developed allowing the transfer of the calculated growth into the mold index. This transformation function, as well as the respective diagram, will be implemented in the biohygrothermal model in the near future. Since both methods of prediction (the VTT model and the biohygrothermal model) are widely used and will continue to be used for some time due to their respective advantages or restrictions, it is important to allow the direct comparison of the results of both methods by the transformation function. This will promote further development of both models and encourage more widespread application of mold growth prediction methods in building practice.

REFERENCES

ASHRAE. 2009. *ASHRAE Standard 160-2009, Criteria for Moisture-Control Design Analysis in Buildings*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Brunauer, S., P.H. Emmett, and E. Teller, E. 1938. Adsorption of gases on multimolecular layers. *Journal of the American Chemical Society* 60(2):309–19.

CEN. 2007. *EN 15026:2007, Hygrothermal Performance of Building Components and Building Elements—Assessment of Moisture Transfer by Numerical Simulation.* Brussels: European Committee for Standardization.

Hens, H., T. Ojanen, H.M. Künzel, G. Dow, C. Rode, and C.-E. Hagentoft. 1996. Summary reports of common exercises in modelling. IEA Annex 24 Final Report, Vol. 1. Paris: International Energy Agency.

Krus, M., H.M. Künzel, and K. Kießl. 1999. Use of advanced measuring and calculative procedures for moisture assessment of building elements. *Trends in Heat, Mass & Momentum Transfer* 5:1–17.

Künzel, H.M., K. Kießl, and M. Krus. 1995. Moisture in exposed building components. *Proceedings of the International Symposium on Moisture Problems in Building Walls*, pp. 258–66.

Künzel, H.M., T. Schmidt, and A. Holm. 2002. Exterior surface temperature of different wall constructions—Comparison of numerical simulation and experiment. *Proceedings: 11th Symposium for Building Physics*, pp. 441–49.

Mücke, W., and C. Lemmen. 1999. Schimmelpilze. ecomed-Verlag, Landsberg am Lech. Landsberg, Germany.

Sedlbauer, K. 2001. Prediction of mould fungus formation on the surface of and inside building components. PhD dissertation, Department of Building Physics, University of Stuttgart, Stuttgart, Germany.

Sedlbauer, K., and M. Krus. 2003. Schimmelpilze in Gebäuden – Biohygrothermische Berechnungen und Gegenmaßnahmen. Berlin: Ernst und Sohn Verlag.

Viitanen, H. 2005–2009. Mathematical modelling of moisture behaviour and mould growth in building envelopes. Espoo, Finland: VTT Technical Research Centre of Finland/TTY Tampere University of Technology, Finland.

Viitanen, H., and T. Ojanen. 2007. Improved model predict mould growth in building materials. Espoo: VTT Technical Research Centre of Finland.

Viitanen, H., and A. Ritschkoff. 1991. Mould growth in pine and spruce sapwood in relation to air humidity and temperature. Uppsala: Swedish University of Agriculture Sciences, Department of Forrest Products.