EVALUATION OF MOULD GROWTH RISK IN APARTMENT HOUSES USING HYGROTHERMAL SIMULATION

Hyeun Jun Moon[1], Seung Ho Ryu[1*], Min Seok Choi[1], Sa Kyum Kim[1], Soo Hyeun Yang[1]
[1]Department of Architectural Engineering, College of Architecture, Dankook University, Yongin-si, Gyeonggi-do, 448-701, Republic of Korea
lemon415@dankook.ac.kr

ABSTRACT

The pollution problems caused by fungi in indoor environments are usually recognized at a stage where colony formation has progressed to a level already enabling visual identification. Thus, the prediction of mould growth risk in early stage is very important for prevention of adverse health effects due to mould growth. This paper presents the results of mould growth risk at specific trouble spots in an apartment house with variation of indoor ventilation rates and internal moisture production using hygrothermal and biohygrothermal simulation approaches. In this research, optimal conditions of ventilation rate and internal moisture production rate are derived to prevent mould growth in residential built environment.

INTRODUCTION

Microbial growth in buildings is one of major causes of Indoor Air Quality (IAQ) problems. Many different fungi species can grow on interior surfaces where moisture and temperature are within favourable conditions. Some of these fungi can cause allergic or toxic reactions, while a few may cause infections to susceptible individuals and cause discoloration and deterioration of building materials (Nielsen, 2003). Especially, in recent years, mould problems in apartment houses have increased due to higher air-tightness, removal of balcony space, and energy-saving design, etc.

The pollution problems caused by fungi in indoor environments are usually recognized at a stage where colony formation has already progressed to a level enabling visual identification. In other words, the prediction and control of the adverse effects of fungi on health at an early stage of fungal growth are usually difficult. It is because of lack of both prediction methods and detailed information regarding the effects of parameters on the mould growth (Jing and Kazuhide, 2010). Thus, the prediction of mould growth risk in early stage is critical for prevention of adverse effects of mould growth.

Several studies have been conducted in recent years to develop mould growth prediction methods. Krus and Sedlbauer (2001) have developed the isopleth systems that represent the requirements for mould germination and growth as a function of temperature and relative humidity in different fungal spores. Sedlbauer (2001) has developed the biohygrothermal model for transient environmental conditions. This model predicts the moisture balance inside a spore with fluctuating boundary conditions. Clarke et al. (1999) have proposed the limit curves of mould growth. In this approach, the principal mould species affecting U.K dwellings were identified and their minimum growth requirements, in terms of temperature and relative humidity, were established. The identified mould species were then assigned to one of six categories of mould species. Kazuhide (2010) has developed a mathematical model that reproduces fungal proliferation and morphological colony formation based on a reaction diffusion modelling approach. In this modelling, fungus are separated in to two states, active and inactive. It is assumed that active fungus moves by diffusion and reaction while generating and producing inactive fungus. Moon (2005) has attempted to develop a probabilistic performance indicator for mould growth risk by treating mould as a risk and a limit state phenomenon. In his study, the mould germination stage is considered a limiting criterion for risk, realized by using a mould germination graph method based on local environmental conditions calculated from hygrothermal models and a standard mould germination graph.

This study aims to investigate the effect of ventilation rates and internal moisture production on mould growth risk in apartment houses. This study conducts an evaluation of mould growth risk using hygrothermal and biohygrothermal simulation at a specific trouble spot in an apartment house with variation of indoor ventilation rate and internal moisture production.

DETERMINING THE HYGROTHERMAL PROPERTIES OF BUILDING MATERIALS

Before hygrothermal analysis for a built environment, a range of detailed physical properties of materials must be known or measured. In general, the material properties such as bulk density of the dry material, specific heat capacity, and thermal conductivity are required for the non-steady computation of the temperature field. The hygric properties that need to be known for building materials include porosity, the water vapor diffusion resistance factor, and moisture storage functions. Some physical properties for common building materials can be found in the literature (Karagiozis et al., 1995). While the database within a software contains properties for materials, there are no data available on domestic building materials. In addition, previous work (Moon, 2010) has shown that differences of hygrothermal properties increase the uncertainty of building simulation. Therefore, it is necessary to characterise building materials used mainly for apartment houses for this specific study. Hence, we conducted an experimental study to determine hygrothermal properties of domestic building materials. Water vapor diffusion resistance factor and moisture storage isotherm were measured. Hygrothermal properties of building materials used for apartment houses including measurement results are shown in Table 1.

Moisture storage isotherms were measured using the method described in EN ISO 12571:2000. This standard specifies two alternative methods for determining hygroscopic sorption properties of porous building materials and products. The first one is a desiccator method using desiccators and weighing cups. The second one is a climatic chamber method. This research determines hygroscopic sorption using the climatic chamber method. The equilibrium moisture contents were measured at five points on each isotherm as well as at saturation. The resulting moisture storage isotherm of gypsum board is shown in Figure 1. The average moisture contents at each relative humidity were entered in a hygrothermal model for simulation.

Water vapor transmission properties were measured using a method described in EN ISO 12572:2001. This standard specifies a method based on cup tests for determining the water vapor permeance of building products and the water vapor permeability of building materials under isothermal conditions. From the measures water vapour transmission water vapour resistance factor, μ, was calculated as the ratio of the vapour permeability of air to the vapour permeability of the material.

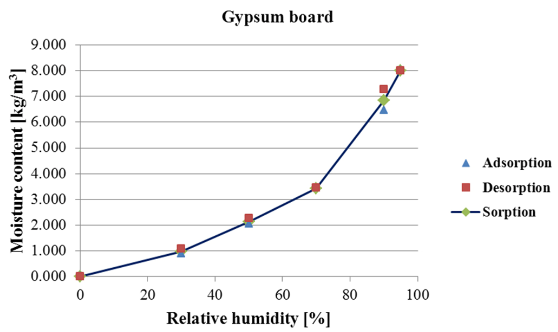

Figure 1 Measured moisture storage isotherms for the gypsum board

HYGROTHERMAL MODEL OF AN APARTMENT HOUSEHOLD

A 15-storey apartment house constructed in 1992 was selected for mould growth risk analysis. The selected building is located in Seoul, Korea, with severe winter and humid summer. The building model consisted of six zones including two bedrooms, a living room, a bathroom, a utility room, and an enclosed balcony. The plan of the selected building is shown in figure 2.

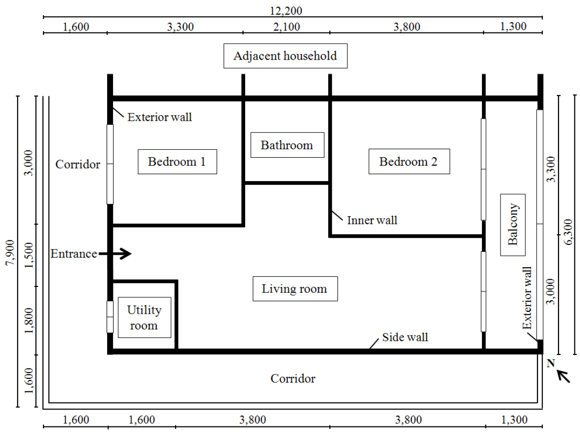

Figure 2 Plan of the selected apartment household

Hygrothermal material properties were taken from the measured data discussed in the previous chapter. Exterior walls consist of concrete, insulation and gypsum board. Sidewall consists of concrete, insulation, gypsum board and wallpaper. Ceiling and floor consist of mortar, concrete and insulation boards. Inner walls consist of concrete. Detailed construction information is shown in Table 2.

The conditioned zones of the selected apartment unit (bed room 1, bed room 2 and living room) are assumed to be heated at 20°C in winter, but no cooling control in summer. The Test Reference Year (TRY) of the Seoul in Korea weather data was used for the exterior boundary condition of the model.

Table 1 Hygrothermal properties of building materials used for apartment houses

	Concrete	Gypsum board	Ceiling board	Insulation board	Particle board	Wallpaper
Bulk density [kg/m³]	2200	600	754	55	600	683
Porosity [m³/m³]	0.25	0.66	0.59	0.86	0.45	0.6
Specific Heat Capacity [J/kg·K]	1000	870	870	1500	1700	1300
Thermal Conductivity [W/m·K]	1.6	0.18	0.18	0.024	0.15	0.17
Water vapor resistance factor [μ, -]	159.79	16.57	18.83	96.78	41.56	833.24

MOULD GROWTH RISK ANALYSIS WITH VARIATION OF VENTILATION RATES AND MOISTURE SOURCES

To evaluate the mould growth risk, detailed hygrothermal conditions on interior surfaces of the building envelope must be known. In this study, WUFI Plus was selected for the whole building hygrothermal simulation (Holm et al., 2003). The mould growth risk was evaluated using a biohygrothermal method within WUFI-Bio (Sedlbauer, 2001). WUFI-Bio is widely used in the field of mould/fungi growth prediction to estimate the probability of growth of some mould species on building materials. In this study, evaluation results of mould growth risk were presented as the mould growth rate and the mould index (Viitanen, 1991).

The procedure for predicting mould growth with biohygrothermal computations is shown in Figure 3. Based on the transient climate conditions at a specific location resulting from a hygrothermal simulation, WUFI-Bio computes the transient water content within a spore according to the moisture storage function of the spore. At each time step, the water content in the spore is compared from temperature-dependent critical water content.

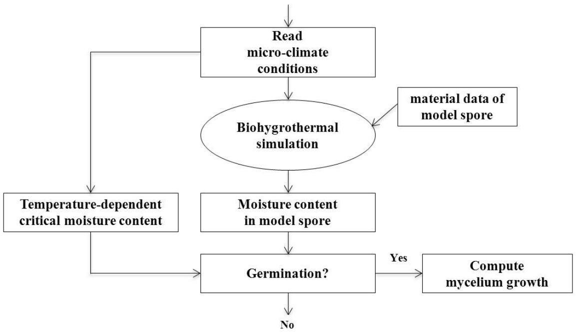

Figure 3 Flowchart detailing the procedure for predicting mould growth with biohygrothermal computations (Sedlbauer, 2002)

Critical water content is determined by means of the isopleths for spore germination as follows: depending on temperature, the lowest relative humidity at which the spore germination takes place can be read off the respective LIM (Lowest Isopleth for Mould) curves in the isopleths. With the help of the moisture storage function valid for the spore inside, corresponding critical water content can be calculated. Once germination has occurred, the mycelium growth isopleth system is used to estimate the growth. Mycelium growth is assumed to be stopped when the water content in the spore falls below the critical water content. However it resumes to grow instantly when the critical water content is exceeded again. In WUFI-Bio, this growth rate is assumed to apply as well to all filaments of the mycelium. The growth rate thus describes by how many millimetres the edge of the infested area moves outward over time; the total growth is then the radius of a mould blotch (Sedlbauer, 2001). Mould index describes the mould-infested fraction of a surface. Table 3 described the detailed mould index.

Table 3 Mould index (Viitanen, 1991)

	Description
0	no growth
1	some growth visible under microscope
2	moderate growth visible under microscope, Coverage more than 10 %
3	some growth detected visually, Thin hyphae found under microscope
4	visual coverage more than 10 %
5	coverage more than 50 %
6	tight coverage, 100 %

In this study, a utility room and balcony space, which has high moisture sources caused by clothes washing and clothes drying, were selected to assess the risk of mould growth. These selected zones are not conditioned in all seasons.

Ventilation rate and moisture source scenario

Several studies have been conducted to identify the dominant parameters that contribute to the mould growth risk (Holm, 2002; Moon, 2010). In our mould risk analysis study, we focus on the ventilation rates and indoor moisture production in the case studies, since these are the ones of the most sensitive parameters in mould growth risk. The amount of indoor moisture sources varies significantly, depending on the type, use, and a configuration of a building. Literature shows a large variation among moisture production rates, even within the same building type, i.e., residential buildings (Yik, 2004). In this study, moisture sources scenarios were established based on the usage of each room. The moisture source scenario of a utility room was based on the number of clothes washing per week. The moisture source scenario of balcony space was based

Table 2 Assembly of building components

	Construction [mm]	U-value [W/m^2·K]
Exterior wall	concrete (200) + insulation (35) + gypsum board (9.5)	0.55
Side wall	concrete (200) + insulation (45) + gypsum board (9.5) + wallpaper (0.5)	0.45
Ceiling	mortar (45) + concrete (45) + insulation (20) + concrete (210)	0.79
Floor	concrete (210) + insulation (20) + concrete (45) + mortar (45)	0.79
Inner wall	concrete (200)	2.6
Window	SHGC : 0.7 [-]	3.4

on the number of clothes drying per week. Moisture generations from occupancy are not considered because the selected rooms are not occupied most of the day. Moisture generation rates of clothes washing and drying referred to 1.96 L/day (10 a.m. – 2 p.m., 490 g/h) and 11.97 L/day (12 p.m. – 6 p.m., 1995 g/h), respectively (Hansen, 1984). The ventilation rate scenario was estimated to be 0.7 air change per hour, referring to the Korean Building Act of 2009 (Korea MLTM, 2009). The ventilation rate scenario was applied to the whole apartment household and was set to be constant natural ventilation during the simulation period. The detailed scenarios of ventilation rates and moisture production rates are shown in Table 4. A total of 25 scenarios were constructed, i.e., V3M3 scenario is 0.7 ACH and 3 times per week of clothes washing/drying in an utility room and balcony space.

Analysis of mould growth risk in an utility room

The hygrothermal conditions (temperature and relative humidity) on the inner surface of the exterior wall in the utility room are calculated using WUFI Plus. The simulation was run for one year at one-hour time step. Figure 4 shows the time courses of temperature and relative humidity on the inner surface of exterior wall in the utility room when V4M2 scenario was applied (1.0 ACH and 1.96 L/week). As a result of the moisture source scenario, the surface relative humidity reaches the peak during the clothes washing period.

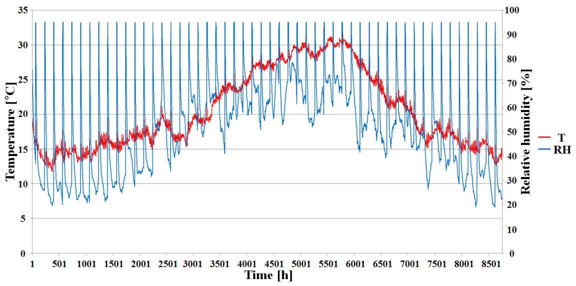

Figure 4 Time courses of temperature and relative humidity on inner surface of exterior wall in the utility room (V4M2 scenario)

These results from hygrothermal simulation were used for the assessment of mould growth risk using the WUFI-Bio. The upper part in Figure 5 shows the computed water content in the spore and the critical water content over time. The lower diagram shows the mycelium growth to be expected after germination.

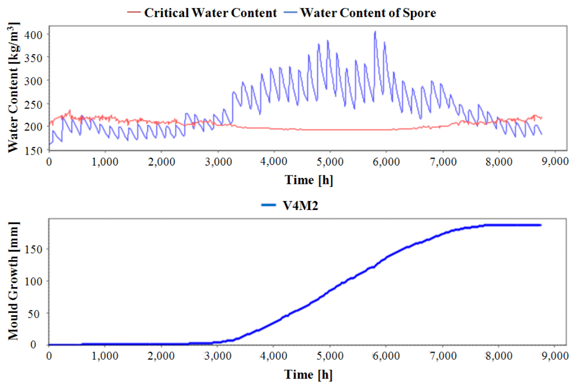

Figure 5 Results of mould growth risk evaluation on inner surface of exterior wall in the utility room (V4M2 scenario)

As shown in the Figure 5, water content of the spore mainly exceeds the critical water content in summer. In other words, mycelium grows mainly in the summer. It is assumed that because of the high relative humidity on the inner surface that cannot be overcome by ventilation due to the high outdoor relative humidity. Figure 6 shows temperature and relative humidity frequency distribution of outdoor air in winter (January) and summer (August) in TRY weather data of the Seoul which is used in simulation.

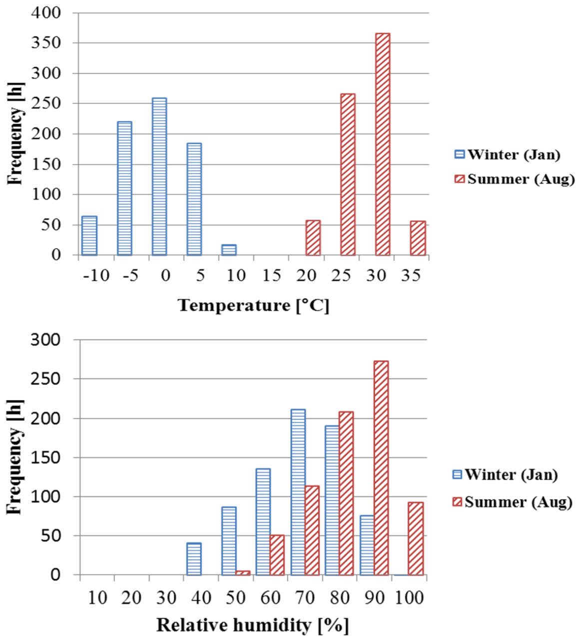

Figure 6 Temperature and relative humidity frequency distribution of outdoor air in winter (Jan) and summer (Aug)

Table 4 Ventilation rate/moisture source scenarios in the utility room and the balcony space

	Ventilation rate			Moisture source		
	Utility room	Balcony space		Clothes washing/drying	Utility room (cloth washing)	Balcony space (cloth drying)
V1	0.3 ACH		M1	0	0	0
V2	0.5 ACH		M2	1 time / week	1.96 L/week	11.97 L/week
V3	0.7 ACH		M3	3 times / week	5.88 L/week	35.91 L/week
V4	1.0 ACH		M4	5 times / week	9.80 L/week	59.85 L/week
V5	2.0 ACH		M5	7 times / week	13.72 L/week	83.79 L/week

As shown in the Figure 6, temperature and relative humidity of outdoor in summer is more higher compared to winter.

Table 5 shows the results of mould growth rate and mould index evaluation for all scenarios. The mould index presented in Table 5 indicates the maximum value occurring during the simulation period. The mould index predicted by the Viitanen model cannot exceed the maximum value of 6. As shown in the table, mould germination and hyphal growth were observed in all scenarios except in the no moisture source scenario (M1). In general, mould growth exceeds 200 mm/year, which corresponds to a mould index of approximately 2, usually not acceptable in built environment (Krus, 2011). In the case of the utility room, to maintain less than 200 mm/year of mould growth rate, ventilation rate should be maintained by more than 1.0 ACH and moisture production rate should be maintained less than 1.96 L/week.

Table 5 Mould growth rates and mould index of all scenarios in the utility room

Mould growth rate [mm/year]						
		Moisture source scenario				
		M1	M2	M3	M4	M5
Ventilation rate scenario	V1	0	433	1513	1692	1775
	V2	0	324	1121	1553	1704
	V3	0	222	811	1393	1596
	V4	0	187	678	1135	1481
	V5	0	117	498	763	1063

Mould index [-]						
		Moisture source scenario				
		M1	M2	M3	M4	M5
Ventilation rate scenario	V1	0	5	6	6	6
	V2	0	4	6	6	6
	V3	0	3	6	6	6
	V4	0	2	6	6	6
	V5	0	1	5	6	6

Analysis of mould growth risk in the balcony

Figure 7 shows the time courses of temperature and relative humidity on the inner surface of the exterior wall in the balcony when V3M2 scenario was applied (0.7 ACH and 11.97 L/week).

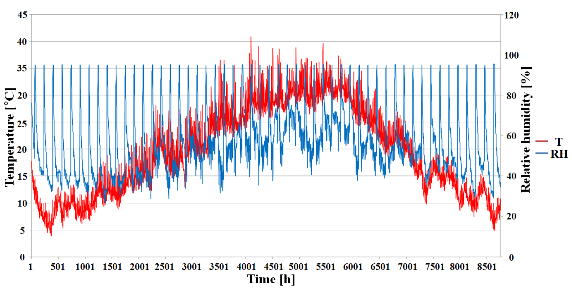

Figure 7 Time courses of temperature and relative humidity on inner surface of exterior wall in the balcony (V3M2 scenario)

As a result of the moisture source scenario, the surface relative humidity reaches the peak during the clothes drying period. Figure 8 shows the computed water content in the spore and the critical water content over time. It also shows the mycelium growth to be expected after germination.

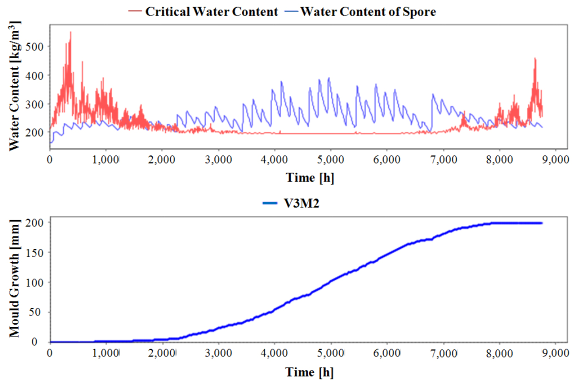

Figure 8 Results of mould growth risk evaluation on inner surface of exterior wall in the balcony (V3M2 scenario)

As shown in the Figure, mycelium grows mainly in summer as well. It is thought that high relative humidity on the inner surface facilitate mould growth in summer also. Table 6 shows the results of mould growth rate and mould index evaluation for all scenarios.

Table 6 Mould growth rates and mould index of all scenarios in balcony space

Mould growth rate [mm/year]						
		Moisture source scenario				
		M1	M2	M3	M4	M5
Ventilation rate scenario	V1	0	331	960	1345	1517
	V2	0	236	717	1149	1416
	V3	0	199	615	997	1302
	V4	0	144	528	856	1143
	V5	0	54	360	584	815

Mould index [-]						
		Moisture source scenario				
		M1	M2	M3	M4	M5
Ventilation rate scenario	V1	0	4	6	6	6
	V2	0	3	6	6	6
	V3	0	2	6	6	6
	V4	0	1	6	6	6
	V5	0	0	4	6	6

The mould index presented in Table 6 indicates the maximum value occurring during the simulation period. In case of the balcony space, mould germination and hyphal growth were observed in all scenarios except in the no moisture source scenario (M1). In the case of balcony space, to maintain less than 200 mm/year of mould growth rate, ventilation rate should be maintained more than 0.7 ACH and moisture production rate should be maintained less than 11.97 L/week

CONCLUSIONS

In this study, we analysed mould growth risk on inner surface of exterior wall in utility room and balcony space. These rooms are one of the trouble spots in an apartment house due to the high moisture sources and low ventilation rate. The main findings from this study are as follows.

Using hygrothermal simulation and mould risk analysis, appropriate ventilation rates and moisture production rates were derived for each type of rooms in an apartment house. According to the simulation results, the utility room in the selected apartment is required to maintain more than 1.0 ACH and should wash clothes less than once a week. The balcony in the selected apartment is required to maintain more than 0.7 ACH and should dry clothes less than once a week. In both cases, the mycelium grows mainly in the summer. Thus, increased ventilation rates and decrease of moisture source in summer should be considered to prevent the adverse effects of fungi.

This paper focused on the effect of variation of indoor ventilation rates and internal moisture production on mould growth risk. The other factors which could affect the mould growth, such as thermal performance of building envelope, hygrothermal properties of materials, HVAC systems will be researched in the next stage of research.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2011-0001031)

REFERENCES

Clarke, J. A. et al., 1999. A technique for the prediction of the conditions leading to mould growth in buildings. Building Environment (34). 515-521.

Hansen, A. T. 1984. Moisture Problems in Houses. Canadian Building Digest, 231 (http://www.nrc-cnrc.gc.ca/eng/ibp/irc/cbd/building-digest-231.html) Access: 2011/May 15.

Holm, A. H., Kuenzel, H. M. 2002. Practical Application of an Uncertainty Approach for Hygrothermal Building Simulations - Drying of an AAC Flat Roof. Building and Environment (37). 883-889.

Holm. A. H., Kuenzel H. M, Sedlbauer, K. 2003. The hygrothermal behaviour of rooms: combining thermal building simulation and hygrothermal envelope calculation. Building Simulation 2003. 499–506.

Jing, J., Kazuhide, I. 2010. Simplified prediction method for fungal growth risk in indoor environment coupled with heat and moisture transfer in building materials. Journal of Environmental Engineering (75), n.653, 603-611.

Karagiozis, A., Salonvaara M, Kumaran M. 1995. Latenite hygrothermal material property database. (NRCC-37908) (IRC-P-3754).

Korea Ministry of Land, Transport and Maritime Affairs. 2009. Korean Building Act.

Krus, M., Seidler, Ch. M., Sedlbaure, K. 2011. Transfer of the mold index on the Biohygrothermal model to mold forecast. Health Engineering (132).

Moon, H. J. 2005. Assessing mold risks in building under uncertainty. Ph.D. thesis. Atlanta, College of Architecture, Georgia Institute of Technology.

Moon, H. J. 2010. Uncertainty analysis in mould spore transportation and its application in an existing building. Indoor Built and Environment (19) no.3, 355–365.

Nielsen, K.F. 2003. Mycotoxin production by indoor molds, Fungal Genetics and Biology (39), 103-117.

Sedlbauer, K. 2001. Prediction of mould fungus formation on the surface of and inside building component. Thesis. University of Stuttgart, Fraunhofer Institute for Building Physics.

Sedlbauer, K. 2002. Prediction of mould growth by hygrothermal calculation. J Therm Envelope Build Science (25), 321-325.

Sedlbauer, K, Krus, M. 2002. Mold growth on ETICS (EIFS) as a result of bad workmanship. J Therm Envelope Build Sci (26), 117-121.

Sedlbauer, K, Krus, M, Breuer, K. 2003. Biohygrothermal method for the prediction of mould growth: procedure and health aspects. Proceedings of the Healthy Building 2003. 666-672.