EVALUATION OF MOULD GROWTH RISKS IN BUILDINGS WITH DIFFERENT HYGRIC PROPERTIES OF INTERIOR FINISHING MATERIALS AND INDOOR MOISTURE CONTROLS

Hyeun Jun Moon[1], Seung Ho Ryu[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

Some fungi species can cause allergic or toxic reactions, while a few may cause infections to susceptible individuals. Some may also cause discoloration and deterioration of building materials. Thus, the prediction of mould growth risk in early stages of development is very important in order to prevent adverse effects due to mould growth. This paper presents the results of mould growth risk analyses at specific trouble spots in an apartment building with variations of the hygric properties of building materials as well as indoor moisture control using hygrothermal and biohygrothermal simulation approaches. In this research, optimal hygric property conditions of interior finishing materials and dehumidification setpoints were derived to prevent mould growth in a residential built environment.

INTRODUCTION

Mould growth in buildings is recognized as one of the main threats that deteriorates the level of IAQ. Mould growth in buildings could increase the risk of adverse health problems (Flannigan, 1991) and could deteriorate the performance of building materials (Nielsen, 2003).

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. Thus, the prediction of mould growth risk at an early stage is critical for preventing adverse effects.

To evaluate the mould growth risk in buildings, different prediction methods can be found in the existing literature. Smith and Hill (1982) have proposed a mould germination graph. The graph was established based on the isopleths of *Aspergillus restrictus*, which were derived from the experiments. 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. Hukka and Viitanen (1999) have developed the VTT model, which is an empirical mould prediction model that expresses growth development by a mould index (M). The mould index ranges between 0 and 6 and is based on regression analysis of a set of measured data. Sedlbauer (2001) has 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. He has also divided building construction materials into four classes according to the type of substrate with respect to the nourishment that the material is able to provide for the fungi. Sedlbauer (2003) extended his isopleth model with the biohygrothermal model, to make a more reliable prediction of the possible mould risk in cases of transient conditions. This model predicts the moisture balance inside a spore with fluctuating boundary conditions. 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 to be a limiting criterion for risk, which is realized by using a mould germination graph method based on local environmental conditions calculated from hygrothermal models and a standard mould germination graph. Jing and Kazuhide (2010) have developed a mathematical model that reproduces fungal proliferation and morphological colony formation based on a reaction diffusion modelling approach. In this modelling, fungus is 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.

This study aims to investigate the effects of building parameters, such as hygric properties of interior finishing materials, ventilation rates and dehumidification have on mould growth risk in an apartment building. This study conducts an evaluation of mould growth risk using hygrothermal and biohygrothermal simulation approaches at a specific trouble spot in an apartment building with variation of the above-mentioned building parameters.

HYGROTHERMAL MODELING OF AN APARTMENT BUILDING

To evaluate mould growth risk, detailed hygrothermal conditions of 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). A unit (size of 66 m^2) in the apartment building, located in Seoul, South Korea, with severe winters and humid summers, was selected for mould growth risk analysis. The building model consisted of six zones, including two bedrooms, a living room, a bathroom, a utility room, and an enclosed balcony. The floor plan of the selected apartment unit is shown in Figure 1.

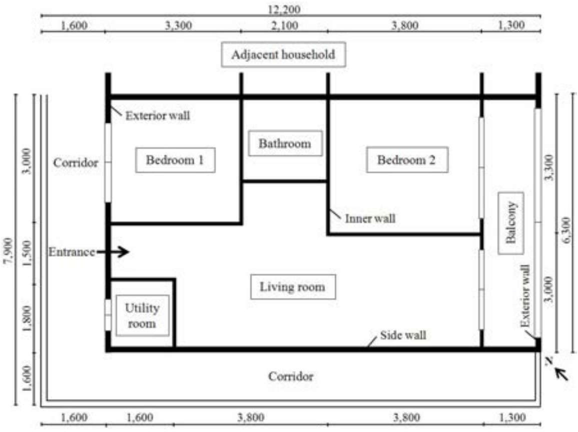

Figure 1 Plan of the selected apartment unit

Hygrothermal properties of building materials used in the model were taken from the data in the literature (Ryu, 2010) and the database in the hygrothermal simulation tool, WUFI Plus. Detailed information about the building materials are shown in Table 1. Exterior walls consisted of concrete (200 mm), insulation (35 mm), gypsum board (9.5 mm) and wallpaper (0.5 mm). Sidewalls consisted of concrete (200 mm), insulation (45 mm), gypsum board (9.5 mm) and wallpaper (0.5 mm). Ceiling and floor consisted of mortar (45 mm), concrete (45 mm), insulation boards (20 mm) and concrete (210 mm). Inner walls consisted of concrete (200 mm).

The conditioned zones of the selected apartment unit (bedroom1, bedroom2, and living room) were assumed to be heated at 20°C in winter and to be cooled at 26°C in summer. The other zones of the selected apartment unit (utility room, balcony and bathroom) were not heated and air conditioned during the simulation period. The Test Reference Year (TRY) for the Seoul, South Korea weather data was used for the exterior boundary condition of the model. The ventilation rate was estimated to be 0.7 air change per hour, which was established in the Korean Building Act of 2009 (Korea MLTM, 2009). The ventilation rate was applied to the whole apartment unit and was set at a constant natural ventilation during the simulation period.

Internal heat and moisture load in occupied zones (bedroom1, bedroom2 and livingroom) were based on the surveyed occupant patterns in the selected apartment unit and the data as described in EN CEN 15251:2007 (CEN, 2007). Internal gain of heat and moisture were only considered by the occupancy schedule. Figure 2 shows the internal heat and moisture load in the living room and bedroom according to the surveyed occupancy schedule.

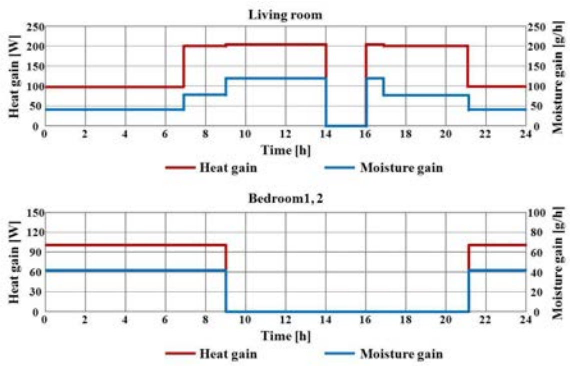

Figure 2 Internal heat and moisture load in living room and bedroom

Internal moisture load in non-occupied zones (utility room and balcony space) were based on the usage of each room. The moisture source of the utility room was based on clothes being washed once a week. The moisture source of the balcony space was based on the clothes being dried once a week. Moisture generation rates of clothes washing and drying referred to 1.96 L (490 g/h during four hours) and 11.97 L (1995 g/h during six hours), respectively (Hansen, 1984). Moisture generations from occupancy are not considered because the selected rooms were not occupied for most of the day.

MEASUREMENTS OF HYGRIC PROPERTIES OF INTERIOR FINISHING MATERIALS

In our mould risk analysis study, we focused on the hygric properties of interior finishing materials, ventilation rates and dehumidification controls. Before analysing mould risk with variations of hygric properties of building materials, we conducted an experimental study to determine the hygric properties of interior finishing materials, i.e., wallpapers. Seven types of wallpapers available on the commercial market were selected for the study.

Table 1 Hygrothermal properties of building materials used for apartment building

	Concrete	Insulation Board	Gypsum board	Wallpaper	Mortar
Bulk density [kg/m^3]	2200	55	600	766	1910
Porosity [m^3/m^3]	0.25	0.86	0.66	0.6	0.25
Specific Heat Capacity [J/kg·K]	1000	1500	870	1300	850
Thermal Conductivity [W/m·K]	1.6	0.024	0.18	0.17	0.8
Water vapor resistance factor [μ, -]	159.79	96.78	16.57	1025.75	45.89

Moisture storage isotherms were measured using the method described in EN ISO 12571:2000 (ISO, 2000). This research determined 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 temperature of the experimental condition in the climatic chamber was 23°C. Three specimens of each wallpaper were tested. The determined moisture storage isotherm of the selected wallpapers is shown in Table 2.

Table 2 Measured moisture content of the selected wallpapers at different relative humidity [kg/m³]

		Relative humidity [%]				
		30	**50**	**70**	**90**	**95**
Wallpaper	**A**	4.28	12.28	25.32	63.56	79.93
	B	5.98	10.29	16.16	32.35	36.27
	C	6.51	10.48	16.13	26.60	27.92
	D	4.26	6.74	10.93	20.21	23.06
	E	6.47	10.79	16.72	31.60	34.90
	F	9.51	14.14	21.71	39.90	46.31
	G	8.51	12.85	19.76	36.54	43.46

Water vapor transmission properties were measured using a method described in EN ISO 12572:2001 (ISO, 2001). This standard specifies a method based on cup tests in climatic chamber for determining the water vapor permeance of building products and the water vapor permeability of building materials under isothermal conditions.

In this study, five specimens of each wallpaper were tested in the climatic chamber which was maintained within ±2% relative humidity around the 50% of relative humidity and ±0.3°C around the 23°C of temperature over the whole test area. In order to ensure uniform conditions throughout the chamber, air velocity in the chamber was also maintained between 0.01 m/s and 0.06. The test specimens were periodically weighted at 24 hour intervals. The weighing continued until five successive determinations of change in mass per weighing interval for each test specimen were constant within 5% of the mean value for the specimen.

For measuring water vapour transmission, a water vapour resistance factor, μ, was calculated as being the ratio of the vapour permeability of air to the vapour permeability of the material. The water vapour diffusion-equivalent air layer thickness, S_d, was calculated as being the water vapour resistance factor multiplied by the thickness of the material. The determined water vapour resistance factor and water vapour diffusion-equivalent air layer thickness of the selected wallpapers are shown in Table 3.

According to the results, the moisture sorption ability of the wallpaper A, F and G are higher than the other wallpapers at high humidity conditions (> RH 70 %). In terms of water vapour transmission, the ability of resistance to moisture transmission of the wallpaper F, G and B are lower than the others.

Table 3 Measured water vapour resistance factor and S_d value of the selected wallpapers

		Water vapour resistance factor, μ [-]	**Water vapour diffusion-equivalent air layer thickness, S_d [m]**
Wallpaper	**A**	1209	0.47
	B	810	0.36
	C	1276	0.60
	D	1026	0.52
	E	1689	0.71
	F	481	0.29
	G	571	0.34

MOULD GROWTH RISK ANALYSIS WITH VARIATION OF BUILDING PARAMETERS

In this study, 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. Evaluation results of mould growth risk were represented in terms of mould growth rate and mould index (Viitanen, 1999).

The computational procedure is based on comparing the water content of the spores under transient climate conditions with the current critical water content. Critical water content is determined by the spore germination isopleths 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.

The spore is assumed to be germinated when the water content in the spore reaches the critical water content. Mycelium growth is assumed to be stopped when the water content in the spore falls below the critical water content. However, it instantly resumes growing when the critical water content is exceeded again. The growth rate describes how much millimetres the edge of the infested area moves outward over time; the total growth is therfore the radius of a mould blotch (Sedlbauer, 2001). The mould index describes the percentage of a surface that is mould-infested. Table 4 describes the details of the mould index.

In this study, a utility room in a non-conditioned zone and a bedroom1 in a conditioned zone, which have high mould growth risk caused by high moisture source and exposure to the outdoors, were selected to assess the risk of mould growth.

Table 4 Mould index (Viitanen, 1999)

Index	Growth rate
0	No mould growth
1	Small amounts of mould on surface
2	< 10 % coverage of mould on surface
3	10 - 30 % coverage of mould on surface
4	30 - 70 % coverage of mould on surface
5	> 70 % coverage of mould on surface
6	Very heavy, dense mould growth covers nearly 100 % of the surface

Analysis of mould growth risk in the utility room

The exterior wall in the utility room was selected as a trouble spot in this study. To investigate the effect of hygric properties of interior materials on mould growth risk, the hygrothermal conditions (temperature and relative humidity) on the inner surface of the exterior wall, when different wallpapers were applied, were calculated using WUFI Plus. The simulation ran for one year with a one-hour time step. The results from this hygrothermal simulation were used for the evaluation of mould growth risk using WUFI-Bio. Table 5 shows the results of mould growth rate and mould index evaluation with different wallpapers.

Table 5 Mould growth risk at the exterior wall in the utility room with different wallpapers

		Mould growth risk	
		Growth rate [mm/year]	Mould index [-]
Wallpaper	A	331	3.99
	B	334	4.02
	C	366	4.30
	D	358	4.23
	E	367	4.31
	F	305	3.74
	G	316	3.85

As shown in the table, in the utility room, mould grew in all cases and the mould index ranged from 3.73 to 4.31. According to the results, there exists an approximately 20 percent difference in mould growth rates with depending on the variation of hygric properties of interior finishing materials. In other words, the wallpaper F that has high moisture sorption ability and low S_d value could reduce 20 percent of mould growth risk comparison with the wallpaper C that has low moisture sorption ability and high S_d value.

However, additional considerations are required since the level of mould growth risk presented in the table is too high. According to the research from Krus (2011), mould growth that exceeds 200 mm/year, which corresponds to a mould index of approximately 2, are usually not acceptable. Mould growth below 50 mm/year, which corresponds to a mould index of approximately 0.5, are usually acceptable.

Additional evaluation of mould growth risk with increasing ventilation rates and dehumidification controls, which could affect mould growth, were conducted using the wallpaper F. Table 6 shows the results of the mould growth rate and the mould index evaluation with the increasing ventilation rate from 0.7 to 1.0 and 2.0 air change per hour. The variations of heating and cooling energy, owing to the increasing ventilation rate, were not considered, because the utility room was not conditioned during the simulation period.

Table 6 Mould growth risk at the exterior wall in the utility room with different ventilation rates

		Mould growth risk	
		Growth rate [mm/year]	Mould index [-]
Ventilation rate [ACH]	0.7	305	3.74
	1.0	249	3.13
	2.0	186	2.20

As shown in the table, although the increasing ventilation rate led to a reduction in mould growth risk, an acceptable level (< 50 mm/year) was not reached. According to the results, mycelium grows mainly in the summer presented in Figure 3. The upper diagram of Figure 3 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. Water content of the spore mainly exceeds the critical water content in summer.

It is thought that despite the increasing ventilation, the high relative humidity in the utility room cannot be diluted due to the hot and humid outdoor air during summer season (Figure 4).

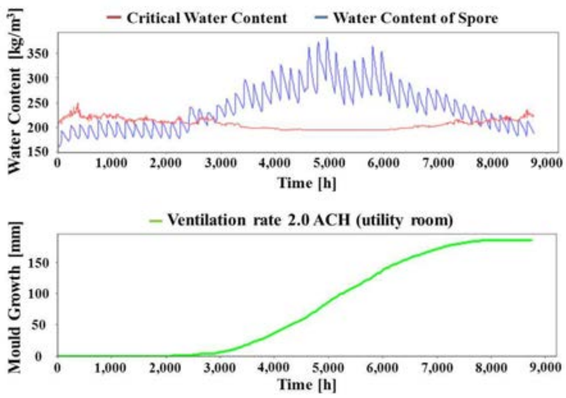

Figure 3 Results of mould growth risk evaluation on inner surface of exterior wall in the utility room (ventilation rate, 2.0 ACH)

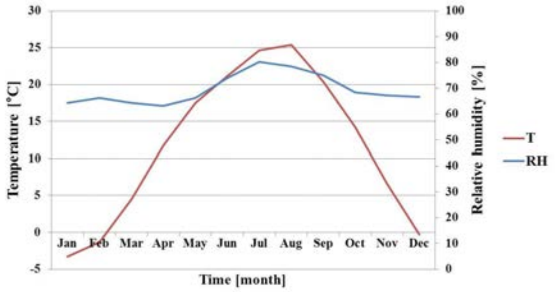

Figure 4 The monthly mean outdoor temperature and relative humidity in TRY data for Seoul

Table 7 shows the results of mould growth rate and mould index evaluations with the consideration of additional dehumidification controls (wallpaper F and 0.7 air change per hour were applied). In the case of the utility room, indoor relative humidity should be maintained below 90 % through additional dehumidification control to maintain an acceptable mould risk level (less than 50 mm/year of mould growth rate).

Table 7 Mould growth risk at the exterior wall in the utility room with different dehumidification controls

Dehumidification setpoints [%]	**90**	Growth rate [mm/year]	33
		Mould index [-]	0.07
		Dehumidification load [kW]	1.4
	80	Growth rate [mm/year]	3
		Mould index [-]	0.01
		Dehumidification load [kW]	3.7

Analysis of mould growth risk in bedroom1

The second case study selects the exterior wall in the bedroom1 as a trouble spot. Table 8 shows the results of mould growth rate and mould index evaluations with different wallpapers.

Table 9 shows the results of heating and cooling load evaluations for the various wallpapers.

Table 8 Mould growth risk at the exterior wall in bedroom1 with different wallpapers

		Mould growth risk	
		Growth rate [mm/year]	**Mould index [-]**
Wallpaper	**A**	123	0.88
	B	123	0.89
	C	124	0.90
	D	124	0.90
	E	124	0.90
	F	122	0.87
	G	123	0.88

Table 9 Energy performance in bedroom1 with different wallpapers

		Energy performance	
		Heating load [kW]	**Cooling load [kW]**
Wallpaper	**A**	535.2	177.9
	B	535.2	177.9
	C	535.1	177.9
	D	535.2	177.9
	E	535.2	177.9
	F	535	177.9
	G	535	177.9

As shown in the table, in case of bedroom1, mould growth was observed in all cases, but there was no significant difference between different wallpapers. It is assumed that the indoor air is heated and cooled to a constant temperature during the simulation period. According to the results obtained from the simulation, there is no perceptible effect on heating and cooling loads between the wallpapers.

Additional evaluation of mould growth risk with increasing ventilation rates and dehumidification controls which could affect mould growth were conducted using the wallpaper F. Table 10 shows the results of mould growth rate and the mould index evaluations while increasing the ventilation rate from 0.7 to 1.0 and 2.0 air change per hour. The variations of heating and cooling loads, owing to the increasing ventilation rate, were also evaluated.

As shown in the Table 10, the increasing ventilation rates are proven to be ineffective in reducing mould growth risk in bedroom1. Meanwhile, the heating load in the bedroom1 increased approximately two-fold due to increasing the ventilation rate from 0.7 to 2.0 air change per hour. It was also observed that mycelium grows mainly in summer, as presented in the Figure 5.

Table 10 Mould growth risk at the exterior wall in bedroom1 with different ventilation rates

Ventilation rate [ACH]	**0.7**	Growth rate [mm/year]	122
		Mould index [-]	0.87
		Heating load [kW]	535
		Cooling load [kW]	178
	1.0	Growth rate [mm/year]	109
		Mould index [-]	0.64
		Heating load [kW]	651
		Cooling load [kW]	166
	2.0	Growth rate [mm/year]	104
		Mould index [-]	0.55
		Heating load [kW]	1038
		Cooling load [kW]	140

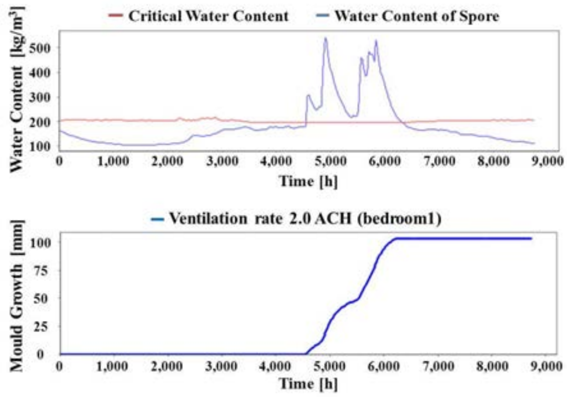

Figure 5 Results of mould growth risk evaluation on inner surface of exterior wall in the bedroom1 (ventilation rate, 2.0 ACH)

Table 11 shows the results of mould growth rate and mould index evaluations with the consideration of additional dehumidification controls (wallpaper F and 0.7 air change per hour were applied). In the case of bedroom1, to maintain an acceptable mould risk level, indoor relative humidity should be maintained below 80% through additional dehumidification control.

Table 11 Mould growth risk at the exterior wall in bedroom1 with different dehumidification controls

Dehumidification setpoints [%]	**90**	Growth rate [mm/year]	101
		Mould index [-]	0.52
		Dehumidification load [kW]	3.8
	80	Growth rate [mm/year]	9
		Mould index [-]	0.02
		Dehumidification load [kW]	26.5

CONCLUSIONS

In this study, we analysed mould growth risk on the inner surface of the exterior wall in the utility room and bedroom1. These rooms are one of the trouble spots in apartment building due to their higher moisture conditions and outdoor exposure. The main findings from this study are as follows.

Using hygrothermal simulations and mould risk analyses, appropriate hygric properties of interior finishing materials and dehumidification setpoints were derived for each type of rooms in an apartment building, in order to maintain an acceptable level of mould growth. According to the simulation results, differences exist in the mould growth rate with variations of hygric properties of interior finishing materials. The non-conditioned zones were more affected by hygric properties of interior finishing materials when compared to the conditioned zones. Also, the wallpapers that had high moisture sorption abilities and low S_d values were advantageous to prevent mould growth.

In the case of the utility room, to maintain an acceptable mould risk level, indoor relative humidity should be maintained below 90 % through additional dehumidification control. In the case of bedroom1, indoor relative humidity should be maintained below 80 % through additional dehumidification control.

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