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Evaluation of a Fungal Spore Transportation in a Building under Uncertainty

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Abstract

A fungal spore transportation model that accounts for the concentration of airborne indoor spores and the amount of spores deposited on interior surfaces has been developed by extending the current aerosol model. This model is intended to be used for a building with a mechanical ventilation system, and considers HVAC filter efficiency and ventilation rate. The model also includes a surface-cleaning efficiency and frequency that removes a portion of spores deposited on surfaces. The developed model predicts indoor fungal spore concentration and provides an indoor/outdoor ratio that may increase or decrease mold growth risks in real, in-use building cases.

To get a more useful outcome from the model simulation, an uncertainty analysis has been conducted in a real building case. By including uncertainties associated with the parameters in the spore transportation model, the simulation results provide probable ranges of indoor concentration and indoor/outdoor ratio. This paper describes the uncertainty quantification of each parameter that is specific to fungal spores, and uncertainty propagation using an appropriate statistical technique. The outcome of the uncertainty analysis showed an agreement with the results from the field measurement with air sampling in a real building.

Keywords: Aerosol Model, Fungal Spores, Uncertainty Analysis, Mold Growth, Indoor Air Quality

1. INTRODUCTION

The mold growth phenomenon in buildings is governed by: environmental conditions (i.e., surface temperature and relative humidity); the exposure time provided by the building systems; and the concentration of fungal spores in a room, which are transported from outside or released from inside the building. This paper addresses a model development for fungal spore transportation in a building with a ventilation system. An uncertainty analysis is also performed to study the effect of uncertainties associated with each model parameter on the outcome of simulation. The effects of environmental condition and exposure time on the mold phenomenon are well-described in Moon (2005a; 2005b). However, the impacts of environmental conditions (temperature, relative humidity) on fungal transportation have not studied at all in mold research community. At this point, we focus on the development of a fungal transportation without consideration of temperature and relative humidity. Once an mathematical model for fungal transportation is established, we will combine the study of environmental conditions and fungal transportation, which is the ultimate goal of this study.

Mathematical models have been developed to study indoor aerosols concentration in relationship with outdoor concentration. Raunemaa and Kulmala (1987; 1989) developed a simple model for particle mass concentration to study the effects of outdoor-to-indoor transport, indoor sources, re-suspension and deposition on surfaces from urban and suburban air-borne particles. Nazaroff and Cass (1991) developed a model for the deposition of air-borne particulate matters in a museum. Kulmala et al. (1999) derived a simple dynamic model to predict indoor air concentration, indoor surface accumulation and the connection between the outdoor and indoor air concentrations of chemically inert aerosols. Although these models provide understanding of the fundamental transportation mechanisms for particulate matters, special attention should be paid to fungal spores' specific parameters, such as: size distribution of spores; cleaning methods and frequency; HVAC systems and filter efficiency; and others. In this paper, the authors extend Kulmala's model to study the transportation and accumulation of "fungal spores" in a building with an HVAC system and regular cleaning activities.

The second part of the paper discusses uncertainties associated with the model parameters. The result of the spore transportation model depends on appropriate values of each parameter in a specific building case. However, selecting the right value of a model parameter is non-trivial, especially for fungal spores, due to size-dependent parameters. In real, existing buildings, it is more complicated, due to various sources of uncertainties, such as natural variations of outdoor conditions or the physical properties of building materials and construction. Therefore, deterministic simulation results under "design-interpreted idealization" always deviate from a building's actual performance. Recent studies on mold growth and uncertainty have shown that simulation is capable of explaining unexpected and non-deterministic mold growth occurrences in buildings (Moon 2005). Uncertainties in hygrothermal simulation, within an envelop system, has also been studied in Holm (2002) and Salonvaara (2001). Results showed that variations of material properties could result in higher variations in moisture contents in the wall. However, no study has been attempted in spore transportation under consideration of uncertainty.

In this paper, we perform an uncertainty analysis with

the developed spore transportation model in a selected building case. By including uncertainties associated with the parameters in the spore transportation model, the simulation results provide probable ranges of indoor concentration and indoor/outdoor ratio. This paper describes the uncertainty quantification of each parameter that is specific to fungal spores, and uncertainty propagation using an appropriate statistical technique. The outcome of both the uncertainty analysis and the air sampling measurements in a real building are compared in this paper.

2. MOLD SPORE TRANSPORTATION MODEL

Model Development

The number of spores in indoor air and those deposited on interior surfaces can both be determined with mathematical models, which assume a complete mixing of air in a room and the equal deposition of spores onto horizontal and vertical surfaces. The other assumption made is that all fungi species have the same physical properties, such as mass, size and diameter.

When a building is not contaminated by fungi, most indoor spores are transported from outdoor air through ventilation or infiltration. The indoor spores introduced into the space deposit on interior surfaces by gravity and removed by external mechanisms, such as cleaning activities or ventilation, or are simply left suspended in the air. External energy, such as wind or human activities, also causes spores to be deposited or suspended in the space. In a building with fungal contamination, the spores are released into the air via the vegetative part of a fungus, consisting of a mass of branching, and threadlike hyphae called the mycelium. Figure 1 illustrates the various spore transportation mechanisms in a building.

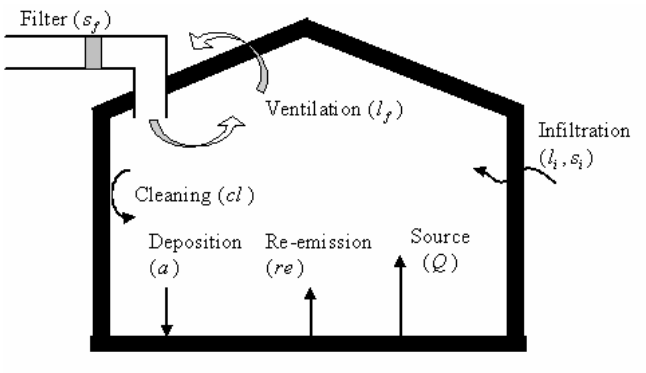


Figure 1. Schematic drawing of spore transportation in a building

In the spore transportation model, the indoor source (Q) represents the release of fungal spores from a mature mycelium. The amount of deposited spores depends on deposition rate(a), penetration factors(s_i), re-emission rate(re), indoor source(Q), ventilation and infiltration rates(l_f, l_i) and outdoor spore concentrations(O). The model includes a surface cleaning efficiency (cl) that accounts for removal of a portion of deposited spores on the surface. An extended model, based on Kulmala's model, has been developed to include ventilation rate(l_f), filter coefficient(s_f) and cleaning coefficient(cl). The time evolution of the indoor fungal spore concentration and deposited spores on a surface can be expressed mathematically as in equations (1) and (2):

$$\frac{dI}{dt} = \left(l_i s_i + l_f s_f\right) \times O - \left(l_i + l_f\right) \times I - aI + reB + Q \qquad (1)$$

$$\frac{dB}{dt} = (aI - reB)\frac{V}{A} \qquad (2)$$

where,

I = indoor air spore concentration (m^{-3})

O = outdoor air spore concentration (m^{-3})

B = the spore surface accumulation on indoor surfaces (m^{-2})

l_i = air exchange rate through infiltration (h^{-1})

l_f = air exchange rate through HVAC (h^{-1})

s_i = penetration coefficient (-)

s_f = filter coefficient, (= 1-filter efficiency, (-))

a = deposition rate (h^{-1})

re = re-emission rate ($m^{-1}h^{-1}$)

cl = cleaning coefficient (-)

cl_f = cleaning frequency (h)

Q = indoor spore sources ($m^{-3}h^{-1}$)

V = indoor volume (m^3)

A = total surface area (m^2)

The first term and the second term in the above equation (1) are modified from the original model and now the extended model can consider the amount of spores through an air handling unit in a given building. This set of ordinary differential equations is solved numerically using Matlab. The authors also introduced cleaning frequency(cl_f) in the model implementation, so that a fraction of deposited spores on building surfaces is removed depending on the cleaning coefficient at a specified cleaning frequency, e.g., 7days. This factor accounts for the effect of cleaning activity by human to remove deposited spores.

Validation and sensitivity of the model

The developed spore transportation model has been validated by Kulmala's model, with the cases and parame-

ters used for a building without HVAC. With the same values of parameter used in Kulmala's paper, the new transportation model was able to show a good agreement. A sensitivity analysis was also conducted to see the effect of each parameter on indoor air spore concentration and spore accumulation using the spore transportation model.

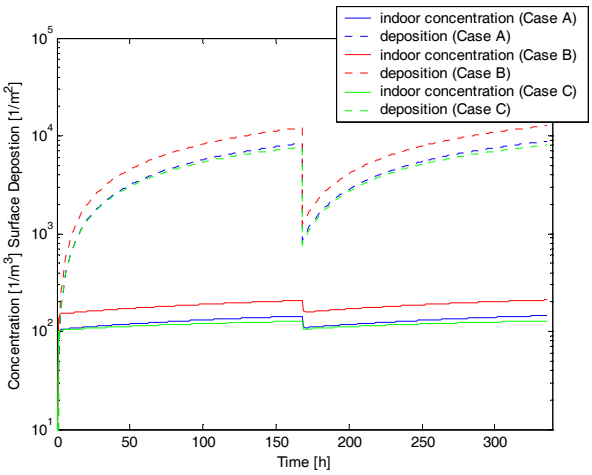
To study the effect of the new parameters (l_f, s_f, cl), four different cases have been conducted in the model parameters. The study building has a Volume/Area ratio of 0.75 and the cleaning frequency of the floor and walls is assumed to occur every seventh day, with a specified cleaning efficiency. Each simulation case ran for two weeks (14 days). Table 1 shows each case and values of parameters used in the analysis. The selected parameter values are for particulate matters used in Kulmala (1999), which are not specific to fungal spores. The values of the new parameters are generally accepted values in building simulation community.

Table 1. Simulation cases and parameter values

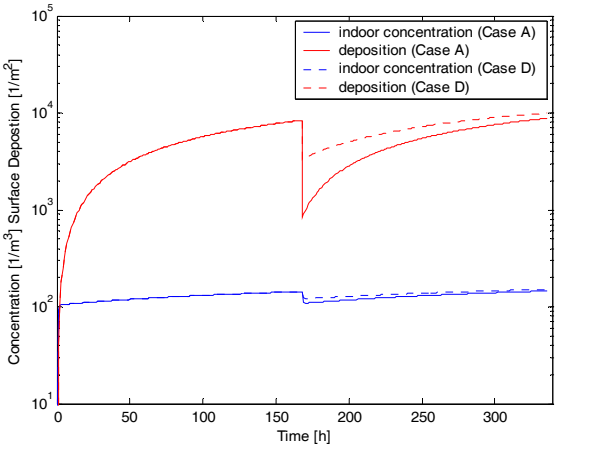
	O	l_i	l_f	s_i	s_f	a	re	cl
Case A	1000	0.25	1.0	0.5	0.1	0.9	0.01	0.9
Case B	1000	0.25	1.0	0.5	0.2	0.9	0.01	0.9
Case C	1000	0.25	2.0	0.5	0.1	0.9	0.01	0.9
Case D	1000	0.25	1.0	0.5	0.1	0.9	0.01	0.6

Figure 2 (a) shows simulation results of indoor concentration and surface deposition as a function of time in the case of A, B and C. As shown, indoor concentration and the amount of deposited spores on interior surfaces are reduced due to surface cleaning on the seventh day. In case B, a high penetration factor in HVAC (i.e., low-filter efficiency) leads to the highest indoor concentration and surface deposition. However, two times increased outdoor air flow rate through HVAC (case C) only decreases indoor concentration and surface deposition slightly. Figure 2 (b) shows the results of case A and D with different cleaning efficiencies. Low-cleaning efficiency leads to higher surface depositions and a slight increase of indoor spore concentrations. These results confirm that the extended model can show the effects of new parameters, and the effect of filter efficiency has bigger effect on indoor and surface concentrations than ventilation. Further analysis of simulation results are dealt with an existing building case later in this paper.

The indoor and outdoor air spore ratio was calculated for each case (Figure 3). Case B, with a higher penetration of outdoor spores through an HVAC filter due to low filter efficiency, showed the highest indoor/outdoor ratio. Higher indoor/outdoor ratio is often regarded as an indicator of possible mold growth problem in buildings. This result suggests that the filter efficiency plays an important role on indoor spore concentration. However, the accuracy of the spore transportation model primarily depends on the selected parameter values. Uncertainties associated with these model parameters are described in the next section.



(a)



(b)

Figure 2. Simulation results for indoor concentration and surface deposition as a function of time, (a) Case A, B and C, (b) Case A and D

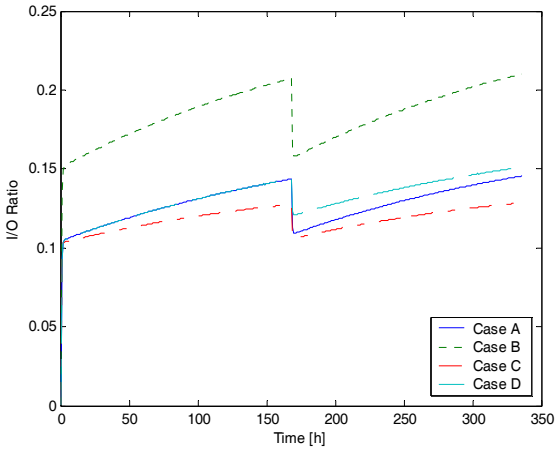


Figure 3. Calculated I/O ratios for each case

3. UNCERTAINTY ANALYSIS IN SPORE TRANSPORTATION

Although the developed aerosol model predicts indoor spore concentrations, its deterministic evaluation cannot provide useful information in a real building case without deeper study on spore-specific parameters. It also requires studying uncertainties associated with the parameters in building spore transportation, which affects the variation of the simulation outcome. For example, outdoor spore concentration always have natural variation and air-filter efficiency shows uncertain values depending on the size of aerosol, age of filter, and so on. These effects can be captured by introducing uncertainty in the fungal spore transportation. Uncertainty analysis can provide more useful information, such as probable ranges of indoor concentration and indoor/outdoor ratio. The effect of each parameter on fungal spore concentration in buildings can also be studied using a parameter screening technique.

The developed aerosol model in this study uses uncertainty analysis to predict indoor/outdoor ratios and indoor air spore concentrations. The uncertainty analysis is case-specific, since the uncertain ranges of model parameters depend on each building. In this paper, the building case is selected from a previous study that reported extensive field measurement data for mold concentration in a building. Burge (2000) conducted extensive air sampling measurements for airborne fungi in a large office building in the U.S. Results revealed the concentration of airborne fungi spores in occupied spaces, mechanical rooms and outdoors. This building is used in our uncertainty analysis and the outcome of the simulations will be compared with the field measurement data. A brief description of the selected building is provided below.

The building is a newly constructed six-story large office building located on the Texas Gulf Coast. This building provides mechanical ventilation for each floor using a duct system. The first floor (2020 m^2) is selected for the detailed simulation under uncertainty and Table 2 shows related building data. A medium efficiency filter with MERV 9 is installed in the building. The detailed description of the filter will be provided later in this paper.

In this field study, Burge reported that the levels of indoor air fungi tended to follow those outdoors, but did not observe distinct seasonal trends, either outdoors or indoors. Mean indoor/outdoor ratio was 0.13 for total fungi and ranged between 0.02 ~ 0.45. Indoor/outdoor ratios at all sampling points were below 0.5, which is a commonly accepted cut-point for non-problem buildings. From the air sampling results, no sample clearly indicated fungal contamination in the building. Indoor concentrations did not exceed 1000 CFU/m^3 and median and geometric mean levels were always below 200 CFU/m^3.

Table 2. Building data for the first floor in the selected building

	Building data	Comments
Floor area	2020 m^2	Total surface area (A) = 4720 m^2
Volume	6060 m^3	Assumed ceiling height of 3 m
HVAC filter	Medium efficiency filter	MERV 9 (the particle size efficiency test method)
No. of occupants	93 persons	
Outdoor air flow rate	1.7 (m^3/s)	

Based on the collected building data, an uncertainty analysis is conducted to show whether our approach provides a compatible outcome with those from the field measurement using air sampling. Uncertain parameters and quantification of those uncertainties are described in the next section.

3.1 QUANTIFICATION OF UNCERTAINTY

The parameters which affect the transportation of fungal spores in buildings include deposition rate, penetration factor, re-emission rate, spore release, outdoor spores and cleaning coefficient, as used in equation (1) and (2). Although other sources of uncertainty are involved in spore transportation in building, as discussed in Moon (2005), this particular study only focuses on the model parameters. This section first describes each parameter and associated uncertainty in the parameters for fungal spores. Since mold-specific parameters are a function of size, the diameters of fungal spores are investigated for dominant fungal species in indoor environment from literature.

The most dominant species indoors reported are Cladosporium, Penicillium and Aspergillus (Burge 2002; Burge, Pierson 2000). The geometric mean diameters of released fungal spores of the three species were investigated by Pasanen et. al (1991). Gorny and Reponen (2001) also reported the aerodynamic diameter of the tested fungal spores. Both experiments showed good agreement for the size of spores shown in the table below. In this particular study, the authors focuses on the three dominant species of spores and range of the diameter of the fungal spores, which is 1.6 ~ 4.6 ㎛. This range is also compatible with the ASHRAE handbook, which reports 2 ~ 5 ㎛ for general fungal spore diameter (ASHRAE 2000).

Table 3. Geometric diameters of fungal spores

Species of fungal spore	Diameters of fungal spores	
	Pasanen 1991	Gorny 2001
Cladosporium sp.	1.6 ~ 4.6 ㎛	1.8 ~ 2.3 ㎛
Penicillium sp.	2.2 ~ 3.9 ㎛	2.8 ~ 3.3
Aspergillus fumigatus	2.0~2.7 ㎛	2.4~2.7 ㎛

Deposition rate (a)

Deposition is the primary mechanism of particle loss in indoor environments, with diameters greater than 1 ㎛ (Thatcher and Layton 1995). The deposition rate accounts for the amount of spores which settle down on the interior surfaces from indoor air by gravity. The rate of deposition can be calculated from the deposition velocity and the aerodynamic diameter of particles, which is fungal spore in this study. According to previous studies, (Kulmala, Raunemaa 1987; Nazaroff and Cass. 1989; Raunemaa, Kulmala 1989), the indoor deposition rate (a) can be calculated using the formula:

$$a = v_D \frac{A}{V} \quad [1/\mathrm{h}] \qquad (3)$$

where,
a is the deposition rate [1/h]
V is the volume of the room
A is the surface area of the room including the ceiling
v_D is the deposition velocity

The deposition velocity is a function of aerodynamic diameter of particles. Existing studies focus on measurements of particle deposition velocities in buildings (Fogh, Byrne 1997; Raunemaa, Kulmala 1989; Thatcher and Layton 1995). However, little research has been done on the deposition velocity of fungal spores. The author assumes the spore deposition mechanism follows one of the particles and uses the diameter of spores to estimate deposition velocities.

Two methods can be used to evaluate the spore deposition velocity. Fogh (1997) developed an empirical model for indoor particle deposition as a function of the particle size, which is a linear regression expression. The other method is Kulmala's (1987) theoretical curve for deposition velocity as a function of the aerodynamic diameter. Based on the empirical model by Fogh and the theoretical deposition velocity curve by Kulmala , the deposition velocity of the spore sizes 1.6 ~ 4.6 ㎛ are calculated in Table 4. The deposition rate for the current case building can also be calculated accordingly. As a result, the deposition rate of 3.4 ~ 28.0 [h-1] is chosen for the case study.

Table 4. Deposition velocities and deposition rate for fungal spores

Particle size	Deposition velocity [10^{-4} m/s]	Deposition rate* [h^{-1}]
Theoretical curve by Kulmala	2.0 ~ 10.0	5.6 ~ 28.0
Empirical model by Fogh	1.22 ~ 3.61	3.4 ~10.1

(*In the current case building, A = 4720 m^2 and V= 6060 m^3)

Penetration factor (s_i)

The penetration factor describes the effectiveness of the building's shell to remove fungal spores entering the building by infiltration. The penetration factor can be determined experimentally by ignoring the deposition rate of indoor particles. A literature review revealed that most building shells do not provide effective filtering against fungal spores. In Thatcher and Layton's study (1995), a penetration factor of one was found, indicating that the building shell was not effective at removing infiltrating particles. Cristy and Chester (1981) also found, from their experiments involving the infiltration of 2 ㎛ aerodynamic spores, that the building shell did not provide any filtration effect. These results were compatible with other studies (Fogh, Byrne 1997) that building fabric filtration was of minor importance. Table 5 shows a collection of the penetration factors found in the literature. The variance of the penetration factors ranges between 0.2 and 0.8, as shown in the table. This wide range of penetration factors is assumed in the uncertainty analysis, since no information on the pressure difference and temperature difference were monitored in the selected case building.

Table 5. Literature review on penetration factors

Penetration factors	References
0.7	Dockery and Spengler (1981)
0.2 ~ 0.4	Freed et.al. (1983)
<0.5	Alzona et. al. (1979)
0.2 ~ 0.6	Thatcher and Layton (1995) without considering deposition loss
0.2 ~ 0.8	Fogh and Andersson (2000)

HVAC filter efficiency (s_f)

A filter's effectiveness at removing spores is expressed as a filter coefficient. The performance of filters varies, based on the size of particles. The filter efficiency of spores also can be estimated based on the size of spores (ASHRAE 1999). Figure 4 shows typical minimum

efficiency curves as a function of particle size. The gray box indicates the range of spore size (2~5 ㎛). In this figure: filter A is a typical filter with MERV 14; filter B is MERV 11; filter C is MERV 9; filter D is MERV 8; and filter E is a typical furnace filter that is below MERV 5 as defined in ASHRAE Standards 55.2 (1999). This classification is based on the particle size efficiency test method.

In this particular study, a medium efficiency filter is used, which is marked as MERV 9. This filter has arrestance of 95% and dust spot efficiency of 25-30% according to ASHRAE Standards 55.2. The range of minimum removal efficiency for the particle size of 2~5 ㎛ reads 0.53 ~ 0.95 in the figure.

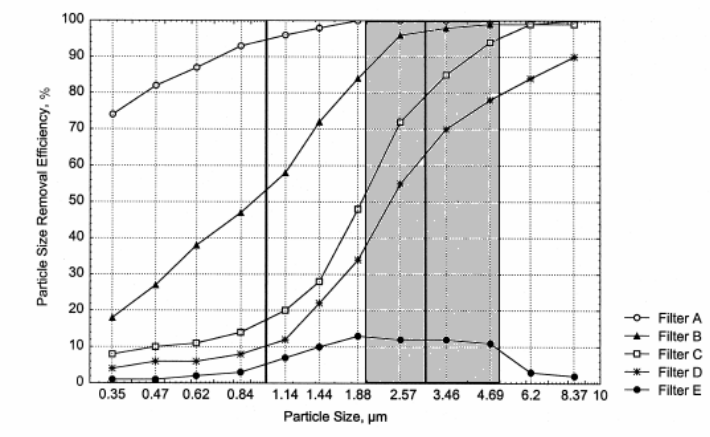


Figure 4. Typical minimum efficiency curves (ASHRAE 1999).

Re-emission rate (re)

Spores deposited on interior surfaces may re-suspend in indoor air, due to human activities, such as sweeping, vacuum cleaning, cooking, walking and sitting. Most of these activities increase indoor air spore concentration. However, the effect of each human activity is difficult to quantify.

In the aerosol model, the re-emission is assumed to be linearly dependent on surface accumulation (B) with a proportionality coefficient. This re-emission coefficient includes the effect of human activity and accumulation time. The size of distribution of reemitted particles differs from the size distribution in deposition. All of these introduce uncertainty in the estimate of re-emission. However, little research has been conducted to estimate the re-emission rate. Kulmala (1999) was able to calibrate his aerosol model by matching the calculated results and field measurement data of fine particles in Helsinki. The study found the re-emission rate of 0.48 1/mh in the space with human activity. In the case of no human activity assumed, he used the re-emission rate of 0.01 1/mh. In this particular study, moderate human activity is assumed. Since no uncertainties associated with the re-emission rate are available, the authors select 0.01~0.48 1/mh, as suggested by Kulmala.

Cleaning efficiency (cl)

Thatcher (1995) showed that cleaning, walking and normal living activity increase indoor airborne particle concentration, due to re-suspension of floor particles. Vacuuming was the highest impact on re-suspension of particles, ranging from 1 to 5 um (Thatcher and Layton 1995). Although cleaning removes a portion of deposited spores on surfaces, it also increases re-suspension of deposited spores indoors. However, Lehtonen and Reponen (1993) reported that vacuum cleaning is an effective way to reduce indoor spore concentration without increasing spore suspension. This is true when a vacuum cleaner is equipped with an exhaust air filter. This study assumes to use a vacuum cleaner in the selected building and investigates its spore removal effectiveness.

Trakumas (2001b) conducted experiments for particle collection efficiencies with size distribution using six types of vacuum cleaners. Results showed up to 50% collection efficiency for 0.35μm particles, which is comparable to the results of Thatcher's (1995) experiment. For the size of 2 ~ 5 μm particles, filter bag type vacuum cleaners showed 96 ~ 99% of collection efficiency, depending on the size of particles. This result was confirmed by chamber experiments by Trakumas (2001a) and Willeke (2001). This range of cleaning efficiency is used for our case study.

Table 6. Summary of uncertain parameters and the lower and upper boundary of each parameter

	Parameters	Lower bound	Upper bound	Comments
1	Outdoor air flow rate (HVAC) (m^3/s)	0.931	1.7	
2	Air infiltration rate (1/h)	0.08	0.5	[2] 50% of the fan-off air change rates
3	Outdoor fungal spores	100	1500	[3] US south region
4	Deposition rate (1/h)	3.4	28.0	
5	Penetration factor (-)	0.2	0.8	
6	Filter efficiency (-)	0.53	0.95	
7	Re-emission rate (1/m·h)	0.01	0.48	
8	Cleaning efficiency (-)	0.96	0.99	

[1] Minimum requirement of ASHRAE Standard 62-2001 for office buildings

[2] U.S. office buildings 0.16~1.0 h-1 (from VanDbronkhorst, 1995)

[3] 25th percentile and 75th percentile data from Shelton 2002

Table 6 shows a summary of the uncertain range of each parameter, including outdoor air flow rate, air infiltration rate and outdoor fungal spore concentration. For air infiltration rate, data collected by VanDbronkhorst (1995) was used for U.S. office buildings. For the variation of outdoor spore concentration, Shelton (2002) collected outdoor spore concentrations in U.S. and reported them by region. The 25th percentile and 75th percentile of outdoor concentration data in the southern region of the U.S. from Shelton's research are used in this case study

3.2 UNCERTAINTY PROPAGATION

The quantified uncertainty is propagated to generate the probable outcome of fungal spore concentration in a given building. The propagation of uncertainties can be performed using various sampling techniques, including the Monte Carlo method and Latin Hypercube Sampling (LHS). LHS is used in our analysis, due to the sampling efficiency and the consideration of parameter distribution.

LHS is a widely-used variant of the standard Monte Carlo method (Wyss and Jorgensen 1998). This approach was well described by De Wit and Augenbroe (2002) and demonstrated to be suitable in building simulation. In this method, the range of probable values for each uncertain input parameter is divided into ordered segments of equal probability. Thus, the whole parameter space, consisting of all the uncertain parameters, is partitioned into cells with equal probability and sampled in an "efficient" manner, in that each parameter is sampled once from each of its possible segments. The advantage of this approach is that the random samples are generated from all the ranges of possible values, thus providing insight into the extremes of the probability distributions of the outputs. In this study, parameter samples were generated using an LHS algorithm in SIMLAB version 2.2 (European Commission - IPSC 2004).

For the implementation of uncertainty propagation, all uncertain parameters are assumed to have normal distributions due to no available additional information on the distribution of each parameter. According to De Wit (2002), this is the first step in uncertainty propagation. Further refinement of uncertainty in parameters should be conducted as long as new information available. Parameter values are selected with 95% confidential interval. LHS, with a sample size of 1000, is conducted in the developed aerosol model. In the simulation, a cleaning frequency of seven days is assumed in the building. The simulation runs for one month.

Figure 5 shows the results of the distribution of the indoor air spore concentrations under uncertainty for the first 14 days. Each line represents one simulation case with selected parameter values. Thus, most indoor concentrations in this case range between 100~300 CFU/m^3 at the end of cleaning frequency (7days), and the maximum concentration did not exceed 1000 CFU/m^3, which is an often-quoted guideline. The calculated mean value is 179.1 and it is compatible to the observation from the field measurement that reported geometric mean levels below 200 CFU/m^3.

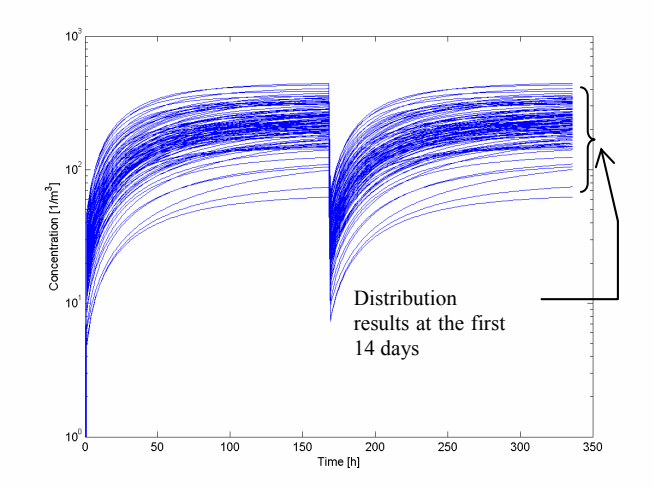


Figure 5. Distribution of indoor spore concentrations under uncertainty in the first 14 days

The distributions of indoor/outdoor ratio are presented in Figure 6. The result show a possible range of 0.01 ~ 0.45, which is similar to the observation from the field measurement (0.02 ~ 0.45). Also, all indoor/outdoor ratios are below 0.5, which is a commonly accepted cut-point for non-problem buildings. Mean indoor/outdoor ratio was calculated as 0.21, which is higher than the one from air samplings (0.13). The discrepancy is due to the assumption of normal distribution of all model parameters. In real buildings, some parameters do not follow normal distribution; for example, infiltration rates in buildings have lognormal distribution. However, lack of detailed information about each parameter distribution prevents further investigation at this time.

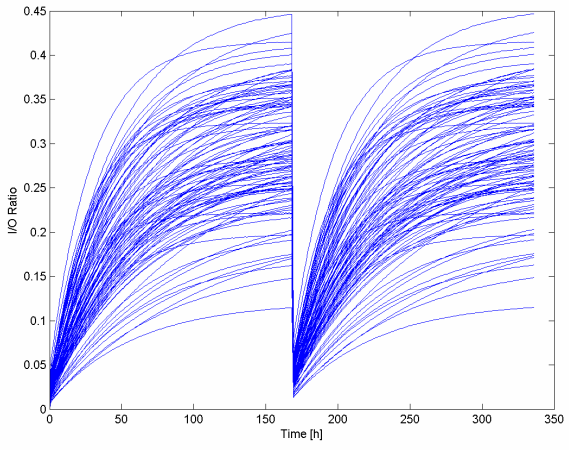


Figure 6. Distribution of indoor/outdoor ratios under uncertainty in the first 14 days

The consideration of uncertainty in the spore transportation model provided a possible range of indoor spore concentration and indoor/outdoor ratio in a given building. The results agree with those collected by field measurement. Our relatively simple model with uncertainty analysis could provide a quick and reliable screening method for investigations regarding fungal spores in buildings.

4. DISCUSSION

The developed spore transportation model can be used to predict indoor spore concentration, deposited spore concentration and indoor/outdoor ratio. The simulation outcome provide crucial information about the assessment of mold growth risk in buildings without expensive filed investigation. However, mold occurrences are influenced by a multitude of parameters with complex physical and biological interactions, such as building materials, water intrusion and rain penetration, design and construction defects, inappropriate HVAC operation and maintenance and other factors. The developed model accounts for only a portion of the mold problem in a building. To accurately address the phenomenon, one needs to consider the presence of random effects and the partly unpredictable interaction between the multitudes of parameters in real-life, "in-use" buildings.

As simulation results show, the indoor/outdoor ratio varies on time and increases after cleaning in the building. This theoretical calculation may differ from actual air sampling results, since it ignores or simplifies complex mechanisms in spore transportation. These include assumptions of: perfect mixed indoor air; fixed infiltration rates by ignoring the effect of outside wind pressure; constant outdoor spore concentration, due to lack of information on daily and seasonal variances; and other factors. Although the current results give critical information for the overall microbial status of the building, a more realistic evaluation can be made by including other source of uncertainties in a systematic approach including scenarios and building usage.

In uncertainty analysis, normal distributions are assumed for all uncertain parameters, due to the lack of information of the distribution of parameter values. Each parameter distribution affects the total variance of the simulation results. Further investigation is required in the parameter distribution for better results from the simulation study. This uncertainty refinement will be conducted as future research.

5. CONCLUSION AND IMPLICATIONS

In this paper, an extended spore transportation model has been developed, which accounts for ventilation rate through an air handing unit and cleaning activity. This spore transportation model could calculate indoor spore concentration, deposited spore concentration and indoor/outdoor ratio. The effects of each parameter can be explained with this model. In an simple sensitivity analysis, results showed that surface cleaning leads to lower indoor and deposited spore concentrations. Simulations also found that the filter efficiency in an HVAC system greatly affects indoor spore concentrations.

This model, with the consideration of uncertainties, can also be used to investigate a building's microbial status. The calculated possible range of indoor spore concentration (179 CFU/m^3) and indoor/outdoor ratio (0.01 ~ 0.45) showed good agreement with the field measurement collected from the same building (below 200 CFU/m^3 and 0.01 ~ 0.45m, respectively). Our approach provides relatively simple and fast screening method that may replace expensive air sampling measurements in buildings. Further research will be conducted for detailed distribution of each model parameter and uncertainty refinement.

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