Transport of fungal spores and particles through a building structure

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ABSTRACT
Penetration of inert particles with a size range from 0.6 to 4 μm and spores of *Penicillium* and *Cladosporium* was studied through a full scale timber structure. Pressure difference and air leakage over the structure were varied. Measurements at moderate pressure differences resulted in the penetration factors within the range of 0.05–0.2 for inert particles, and they also indicated the penetration of fungal spores through the structure. The determined penetration factors depended highly on pressure difference over the structure. The findings in the experiment suggest that a mechanical exhaust ventilation causing a negative pressure inside the building may elevate the risk of microbial contamination of indoor air if that exists in the crawl space or in building envelope.

INDEX TERMS
Air infiltration; Fungi; Leakages; Particulate matter; Pressure difference

INTRODUCTION
Microbiologically clean buildings probably do not exist as some contamination in the structures is built up already during the construction process. The level of fungal spores in the crawl space might be several orders of magnitude greater than indoors. In the contaminated crawl spaces, the spore densities elevated up to a range of 10^3–10^5 colony-forming units per gram (cfu/g) of material of wood-based boards and on timber (Kurnitski and Pasanen, 2000). Under heavy fungal colonization, airborne spore concentrations were up to 10^3–10^4 cfu/m^3. If the floor structure is not air-tight the air flow through a structure might transport particles and thus will have an influence on indoor air quality.

Typical indoor under pressures with mechanical exhaust ventilation are within the range of 5–20 Pa. A field study (Kurnitski, 2000) showed high air flow rates through leaks in the floor to the apartment at the pressure difference of around 6 or 15 Pa which depended on the operating speed of exhaust fan. Field measurements (Mattson, 2002; Airaksinen *et al.*, 2003) have shown evidence of fungal spores transportation from crawl space to indoors. In this work penetration of particles was studied in a laboratory setup with a common building structure. Particle type, air leakage and pressure difference were varied.

METHODS
To measure the particle penetration a full-scale floor structure with dimensions of 2.2 m by 2.2 m was built in the laboratory. The floor was located between two chambers; CH1 corresponds to indoors and CH2 to crawl space as shown in Figure 1. The floor had 20 cm mineral wool insulation (rock wool with volume weight of 30 kg/m^3), 12 mm chipboard in the indoor chamber (CH1) side and 13 mm porous fibre board in the CH2 side, Figure 2. As the gravitational force has a minor importance for small particles, the floor was twisted 90° for practical reasons. The air was exhausted only from CH1 forcing the flow through the floor. To control the pressure difference between chambers a supply airflow rate to CH1 was controlled. The supply air to the CH2 was filtered by using HEPA filter, and it flowed through

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a diffuser to ensure that the supply air is fully mixed in the CH2. To ensure that the particles were fully mixed in the air of the CH2 the concentration of particles were measured at three different heights (70, 110 and 190 cm from the bottom of the chamber).

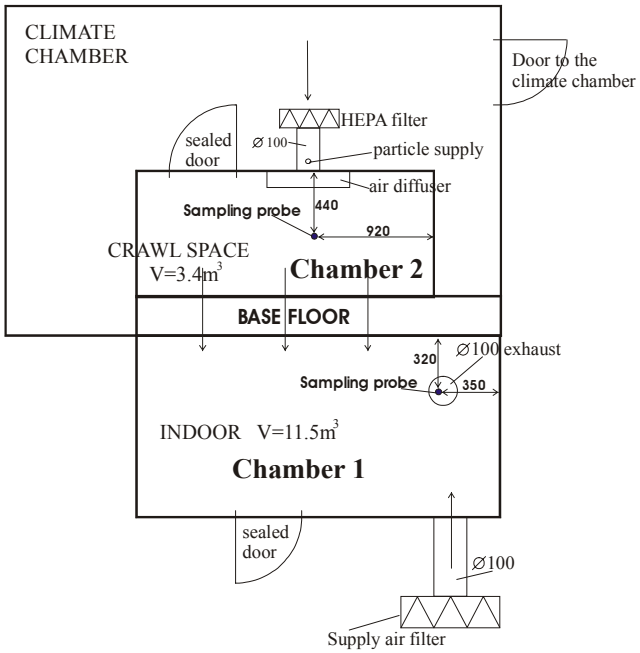

Figure 1 Chamber 1 and 2, and the placements of sampling probes.

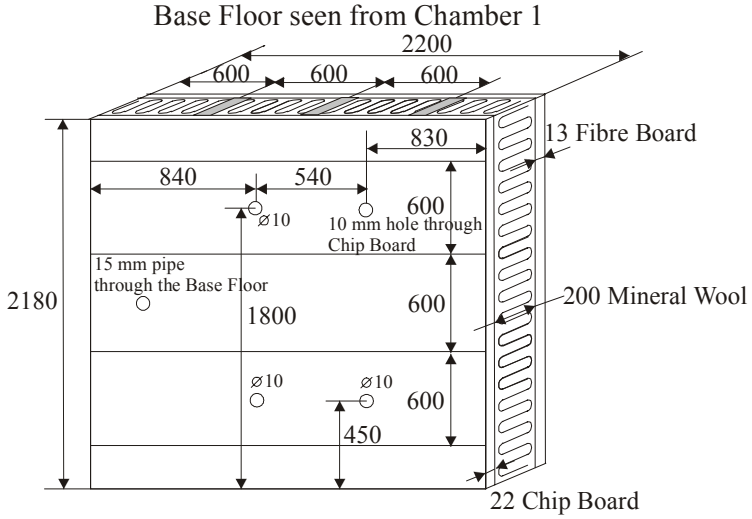

Figure 2 The construction of the floor (dimensions in mm).

Air leakage of the wooden floor was varied with different penetrations as shown in Table 1.

Table 1 Characteristics of tightness of floor structures in the study

Test floor	Description	Air leakage	
		$m^3/h/m^2$	ach[a]
No penetrations	Neither penetrations nor holes in the floor	0.88	1.0
Capped Ø15 mm pipe	15 mm copper pipe penetrating the floor, to simulate that the sealing of the construction was not made in accordance with the best practice. Copper pipe itself capped thus no particle could flow through pipe	0.83	1.0

Ø10 mm holes in the surface boards[b]	Four 10 mm holes both in the fibreboard and chipboard at opposite locations to each other. The holes only in the boards, mineral wool insulation stayed untouched	1.16	1.4
Ø13 mm holes in the surface boards[c]	Three 13 mm holes both in the fibreboard and chipboard at opposite locations to each other. The holes only in the boards, mineral wool insulation stayed untouched	2.03	2.4
Open Ø15 mm pipe	15 mm copper pipe was open, i.e. the air in CH2 could flow through the pipe to CH1	1.19	1.4

[a]Air leakage value air change per hour is an illustrative air leakage value of whole apartment which is calculated by considering an apartment with dimensions $10 \times 10 \times 2.5$ m^3 and the same leakage area as in the floor for all surfaces.

[b]The structure is used only in the case of inert particles.

[c]The structure is used only in the case of *Penicillium* and *Cladosporium.*

Penetration Factor

In this study the penetration factors for inert particles were calculated from the mathematical model given by (Kulmala *et al.*, 1999)

$$V\frac{\mathrm{d}C_1}{\mathrm{d}t} = s_\mathrm{f}\cdot\dot{V}_2\cdot C_2 - \dot{V}_1\cdot C_1 - a\cdot C_1\cdot V + re\cdot B\cdot V + Q \qquad (1)$$

where V is the volume of the room (m^3), C_1 the particle concentration in CH1 (m^{-3}), t the time (s), s_f the penetration factor from CH2 to CH1 (–), $\dot{V}_2$ the air flow from CH2 to CH1 (m^3/s), $\dot{V}_1$ the air flow from CH1 to outdoors (m^3/s), C_2 the particle concentration in the CH2 (m^{-3}), a the deposition rate (s^{-1}), re the re-emission rate (m^{-1} s^{-1}), B the particle surface accumulation on indoor surfaces (m^{-2}), Q the sink or source of particles indoors (s^{-1}). The deposition rate was calculated from

$$a = v_\mathrm{d}\cdot\frac{A}{V} \qquad (2)$$

where v_d is the deposition velocity (m/s), and A the total indoor surface area including furniture etc. (m^2).

Since the measurements were done in the test chambers with clean surfaces, the re-emission rate was assumed to be zero.

In recent studies of buildings or room-sized chambers the reported deposition velocities have a wide range (Lai, 2002), thus, there is considerable uncertainty in the typical values of deposition velocities for buildings. In this study, the deposition velocity used was adapted from results reported in Xu *et al.* (1994) and Thatcher *et al.* (2002), and it is extrapolated with theoretical predictions by Lai and Nazaroff (2000). The same deposition velocity is also used in Fisk *et al.* (2002). Deposition velocity used here is valid for particle diameters between 0.3 and 8 μm.

$$v_\mathrm{d} = 3\times10^{-5}\cdot(d_\mathrm{p}\cdot10^6)^{1.58} - 1\times10^{-6} \qquad (3)$$

where d_p is the diameter of the particle (μm).

For *Penicillium* and *Cladosporium* it was not possible to achieve steady state concentrations with equipment used and therefore, the penetration factor was estimated as a percentage of the particles penetrated through the structure.

$$s_{\mathrm{f},\%} = \frac{C_1}{C_2}\cdot100 \qquad (4)$$

Inert Particles

In the laboratory measurements, six different sizes (0.6, 1.3, 2.5, 4, 7 and 15 μm) of inert monodisperse latex (polystyrene) particles produced by Duke Scientific Corporation were generated to the CH2. The particle supply flow to the supply air channel of the CH2 was 3 l/min. The pressure difference between chambers was either around 6 or 20 Pa. The concentration of particles was measured continuously by using optical particle counter (Climet LI 500) in both the chambers. The size ranges of the optical particle counter were 0.3–0.5, 0.5–1.0, 1–5, 5–10, 10–25 and ≥25 μm. The pressure differences between CH1, CH2 and laboratory hall was measured, and the air flow rate to the CH2 and air flow rate from the CH1 was logged in intervals of 1 min.

Penicillium and *Cladosporium*

Spores of *Penicilium crustosum* and *Cladosporium spaerospermum* were supplied to CH2 by using circulating air, thus the supply did not affect the air change rate of CH2. The pressure differences between the chambers were 6 and 18 Pa. The concentrations of airborne fungal spores were measured in the both chambers by using six-stage cascade Andersen impactors; and three successive samples were taken from the both chambers. The fungal spores were collected on 2% malt extract agar (MEA). The sampling times are shown in Table 2. The incubation time of the samples was 5–7 days at 25°C. The concentration of particles was also measured continuously by using optical particle counter in the both chambers. The sampling time for optical particle counter was one minute.

Table 2 Sampling time of different measuring case

Microbe	Floor	Pressure (Pa)	Chamber 2 samples	Chamber 1 samples
Penicillium	Ø13 mm holes in the surfaces	18	3 × 5 min	3 × 10 min
	No penetrations	18	3 × 1 min	3 × 5 min
	No penetrations	6	3 × 1 min	3 × 5 min
	Ø13 mm holes in the surfaces	6	3 × 1 min	3 × 5 min
Cladosporium	Ø13 mm holes in the surfaces	6	3 × 1 min	3 × 5 min
	Ø13 mm holes in the surfaces	18	3 × 1 min	3 × 5 min
	No penetrations	18	2 × 30 s, 1 × 1 min	3 × 1 min
	No penetrations	6	2 × 30 s, 1 × 1 min	3 × 1 min

RESULTS

The penetration factor s_f was calculated from Eqn (1); penetration from laboratory hall was assumed to be zero, since the chambers were well sealed. The results in Table 3 show that there are very small differences relative to the air flow paths of the first three cases for particles of 0.6, 1.3 and 2.5 μm. Smaller particles show only slightly higher penetration factor. This indicates that holes in the surface boards of the structure (which increase air leakage only from 1 to 1.4 ach) do not affect penetration of these particles. The material layer unchanged in these cases, mineral wool and probably especially its surface contacts, is likely to dominate the penetration of these particles. The penetration factor 0 for 4 μm seems to confirm the importance of mineral wool layer (and its installation) for particles. For 4 μm particles mineral wool already acts as a perfect filter. Last structure with an open pipe (Ø15 mm) shows completely different performance with much higher penetration factors for all particles. All results in Table 3 stress the importance of pressure difference across the structure. The higher

pressure difference the significantly higher penetration factors for all structures and particles studied.

Table 3 Penetration factors for the floor structure with different airflow paths and pressure difference

Test floor	Pressure difference (Pa)	Penetration factor with different size of the supplied particles (–)			
		0.6 µm	1.3 µm	2.5 µm	4 µm
No penetrations	20	0.19	0.19	0.18	
	6	0.12	0.08	0.06	
Capped Ø15 mm pipe	20	0.20	0.20	0.16	0
	6	0.08	0.07	0.05	
Ø10 mm holes in the surface boards	20	0.14	0.15	0.10	0
	6	0.06	0.03	0.02	0
Open Ø15 mm pipe	20		1.0		0.47
	6		0.54		0.19

Most of the spores of *Penicillium* were impacted on stage 4 corresponding mean geometric diameter of 2.6 µm. Spores of *Cladosporium* were mainly impacted at stages 4 and 5 corresponding to mean geometric diameters of 2.6 and 1.4 µm. During the test of *Cladosporium,* which was carried out 21 h after the test of *Penicillium,* the spores of *Penicillium* were still detected. As can be seen in Table 4, the pressure difference has a great impact on penetration.

Table 4 Penetration of spores (%) of *Penicillium* and *Cladosporium* from CH1 to CH2 detected with Andersen impactors

Test floor	Pressure (Pa)	Supply of *Penicillium* Detected *Penicillium*	Supply of *Cladosporium* Detected *Cladosporium*
No penetrations	18	5.64	24.08
	6	1.44	5.32
Ø13 mm holes in the surface boards	18	–	49.81
	6	2.99	2.04

DISCUSSION AND CONCLUSIONS

The equation of penetration factor (1) applies for inert particles. Possible source of uncertainty in inert particle calculation is the assumption that the penetration through all other parts of CH1, except the studied floor, is zero. This was avoided by careful tightening of CH1. The estimation of penetration of fungal spores is more complicated since they can agglomerate and some of them are sticky in the surfaces, also the shape of microbial spores is not spherical for all species. As measured results were indicative for fungal spores (steady state was not achieved), more detailed analyses should be carried out in further studies.

Although the uncertainty caused by estimated deposition velocity is high and affects on penetration factor highly, the results show that both inert particles and fungal spores are penetrating a typical floor construction. Penetration of fungal spores is difficult to control by sealing building envelope. The only effective way to avoid penetration seems to be balancing or even pressurizing the building. However, in cold climate moisture condensation risk should be taken into account. Determined penetration factors depended highly on pressure difference indicating that mechanical exhaust ventilation causing under pressure in the building may cause health risk if some contamination in the building envelope exists.

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