Ventilation and building related symptoms

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SUMMARY

Due to criteria for building energy efficiency today's buildings are better insulated and the envelope is more air tight. These improvements have led to a more comfortable buildings and lower running costs. However, the new indoor environments are more dependent on controlled ventilation system thus, the role of ventilation is emphasised.

Impurities in indoor air can originate from different sources: e.g. materials, structures, adjacent zones such as crawl spaces or attics or ventilation systems. Ventilation and pressure differences as well as leakage routes are key factors in understanding the concentrations of impurities in indoor air and their penetration to indoor air. This paper reviews the current understanding of the relationship between ventilation and its effect on sick building syndrome.

INTRODUCTION

In epidemiological population studies, moisture damage and microbial growth in buildings have been associated with a number of health effects, including respiratory symptoms and diseases and other symptoms [1-4]. The health effects associated with moisture damage and microbial growth seem to be consistent across different climates and geographical regions [5-8].

Microbiologically clean buildings probably do not exist, as some contamination in the structures begins to build up even during the construction phase. In the case of moisture damage, even after repairs, a significant amount of contaminated materials can remain in structures [9]. Therefore, the potential transport of pollutants from and through structures has great importance in respect of the design and construction of buildings. It is important to know which factors affect the release and penetration of pollutants and possible measures, such as sealing and pressurising, that can be taken to avoid this.

Ventilation does not directly affect on occupant health or perception outcomes, but the rate of ventilation affects indoor environmental conditions including air pollutant concentrations that, in turn, may modify the occupants' health or perceptions. The air pollutant concentrations in a given space depend on several factors other than air flow rate.

In steady state conditions where the ventilation air is well mixed to indoor air the concentration of indoor air can be calculated from simple balance equations. In practice, however the situation is not that simple. Typically pollution source is not uniform and mixing not complete thus, the concentration of pollutants in breathing zone may vary significantly depending on the air distributions pattern and the locations of the pollutant sources. Also the indoor pollutant generation rate (source strength) is usually not constant and has very high variations. Pollutants may be adsorbed by room surfaces during high concentration periods. Therefore non emitting surfaces may be emitting sources. Indoor pollutant source strengths are highly variable among buildings, and considered the biggest cause of the variation in pollutant concentrations among buildings [10].

In many buildings, ventilation rates are not constant. Often old residential buildings are running with a natural ventilation thus, the climatic conditions are strongly affecting on ventilation rates. Typically in office buildings ventilation systems may not operate at night or are operated at reduced level, and the rates of ventilation during operation may change with internal heat loads or with outdoor air temperature. Since the reduced night ventilation is usually created only by using exhaust fans, the pressure difference over the building is also dramatically changing between day and night. Pollutant concentrations may not reach equilibrium or they reach that until several hours after ventilation rates stabilize. Thus, the indoor air quality is also dependant on the operating schedule of the ventilation system.

In addition to above mentioned factors, the concentration of pollutants in indoor air is affected by following other major forces: the level and type of pollutants outdoors, possible recirculation of return air, the location of the outdoor air intake relative to outdoor air pollution sources including exhaust air outlets, pollution sources in the air handling unit, and pollutant removal from supply air filters, sorbents or deposition on duct surfaces. Therefore with a same ventilation rate indoor air quality may vary significantly due to variations in the quality of the supply air [11,12].

VENTILATION, PRESSURE DIFFERENCE AND PENETRATION OF IMPURITIES

Residential buildings often have mechanical exhaust ventilation, where intake air comes through inlets and cracks. In cold climates, inlets will cause a draught in winter and they are often closed, resulting in a high under-pressure indoors and forced airflow through cracks. Typically, mechanical exhaust ventilation creates an under-pressure of 5-10 Pa in the apartment [13] if the inlets are open. A field study [14] showed high air flow rates through leaks in the base floor to the apartment at a pressure difference of around 6 or 15 Pa, depending on the speed of the exhaust fan. Field measurements [15,16] have shown evidence of fungal spores transported indoors from a crawl space. According to a literature review by [4], concentrations of viable fungi in the indoor air of residential buildings vary between 10–100,000 cfu/m^3. Although the range is wide, average levels of 100–10,000 cfu/m^3 are typical. Lower levels have been reported in winter not only in a cold climate [17] but also in a subtropical climate [7].

Concentration of fungal spores and ventilation system

Many studies have proven that the concentration of microbes outdoors is clearly higher in summer than in winter. However, there is only a very limited number of reports on concentrations in the crawl spaces or attics, even though impurities might be transported from there as well. Especially crawl spaces could have favorable conditions for fungal growth especially in the summer, when the outdoor air is usually warmer and has a higher moisture content, which is transported via ventilation to the crawl space. The extra moisture condensates to the surfaces in the crawl space giving better conditions for microbes in the surfaces.

The concentrations of viable fungal spores in the crawl spaces were a few thousand cfu/m^3 [16]. There are no guidelines or sufficient reference data in Finland for the concentration of fungal spores in crawl spaces. The high concentrations of fungal spores in the air under the floor may exposure occupants to fungal spores or fungal metabolites if there are cracks or holes between the spaces.

In subartic climate, in summer the concentration of fungal spores indoors is usually smaller than the concentration outdoors, whereas in winter the indoor/outdoor –ratio often is over 1 in the apartments as well as in the offices [18]. Generally outdoor air is the main source of fungal spores and the seasonal variation is wide; three to four order of magnitude in subartic climate (Finland), [e.g. 19,16] .

Indoor/outdoor –ratio had been higher in buildings with mechanical exhaust ventilation than in buildings with mechanical supply and exhaust ventilation [e.g. 19]. In a study [16] such a relationship couldn't be found. A reason for this might be that in this study all the measured buildings with mechanical supply and exhaust ventilation were primary schools or day-care centres, and the measurements were done during the working day and the influence of outdoor air to indoor air concentrations could not be avoided. Also the clothes of the children might be a potential carrier of spores [20].

Transport of fungal spores indoors

It has been found out in many studies that in indoor air particle concentration is highly influenced by outdoor particle concentration. Also the type of the particles is similar. According to [16] the total concentration of fungal spores did not correlate statistically between indoor and crawl space but higher concentrations in crawl spaces could be seen elevated concentrations indoors as well. Crawl space concentrations of fungal spores were tens or thousands of times higher than indoors.

However, when specific species of fungal spores were examined a relationship was found in Acremonium which is not typical microbe indoors, indicating presence of high counts in crawl spaces reflecting as high counts in indoor air.

The size of a particle has an important role in respect of penetration of a crack in a building envelope, thus, it is important to study the size distribution of fungal spores to estimate their penetration indoors. The size distribution is varying depending on microbial species. According to [16] fungal spores analysed from indoors, outdoors and crawl space were similar in shape when size distributions were compared. The highest counts were impacted (Andersen) in stages whose average aerodynamic diameter was between 1.4-2.6 µm. This size range is interesting as the alveolar deposition of particles above 0.5 µm has a maximum at about 3 µm. Therefore, even small changes in particle size around this maximum value effect on the deposition pattern of particles [21].

There are many factors affecting the size of fungal spores such as age, dehydration, agglomeration and relative humidity of surrounding air. In a study [21] it was found out that the most common fungal spores, such as *Penicillium, Cladosporium, Aspergillus* and yeasts, have their maximum concentrations in the size range 2.1 – 3.3 µm. In this study, the maximum counts were observed in smaller fungal spores, between 1.4 – 2.6 µm, indicating that the fungal spores are mainly detected as single spores and not as aggregates.

Air change rate and air flow patterns

In [22] it was found out that the levels of airborne microbes were higher in naturally ventilated office buildings than in offices with mechanical ventilation. In a wide review by [23] it was found out in that there is a strong evidence between ventilation and the control of air flow directions in buildings and the transmission and spread of infectious diseases such as measles, TB, chickenpox, anthrax, influenza, smallpox, and SARS. However, they didn’t found data to support the specification and quantification of the minimum ventilation requirements in schools, offices and other environments in relation to the spread of airborne infectious diseases.

Particles and their penetration indoors

It is not only the moisture and microbes which can cause problems, but also exposure to fine particles. According to recent studies particles smaller than 2.5 µm in diameter can reach the lower respiratory system and cause adverse health effects [24,25]. However, usually the limit value for respirable particles is considered between 2.5-5 µm. Comite European de Normalisation (CEN 1992) and International Organization for Standardization (ISO 1992) both define the limit value for respirable particles 4 µm. It is still unclear what causes the health effects of such particles, but it seems that the type of particle has some role. According to studies [26,27] sand dust is not so harmful as particles of the same size originating from the combustion of fuels. About 70-90% of the viable fungi in indoor air have been estimated to be in the respirable size fraction [7]. The median aerodynamic diameter for fungi in indoor air is typically 2-3 µm [28]; the highest concentrations of airborne viable fungi are also usually in the same size range.

A number of studies have focused on properties of ambient particulate matter in recent years. Elevated concentrations of aerosol particles have been associated with increases in mortality as well as adverse health effects [29] Even though the particulate matter outdoors and its penetration indoors is very important topic, it is typical for all kind of buildings and not specific to buildings with SBS symptoms.

Many studies have been carried out to estimate the penetration of particles through cracks. [30] report penetration factors of 0.5-0.8 for particles in a size range of 0.5-2.5 µm. [31] found that at a pressure of 5 Pa 40% of 2-µm particles and <1% of 5-µm particles penetrate through horizontal slits of a height of 0.5 mm. In a study by [32] particles of 0.1-1.0 µm are predicted to have the highest penetration efficiency, nearly unity for crack heights of 0.25 mm or larger at a pressure difference of ≥4 Pa. These results are important, since the peak of the size distribution of fungal spores is often between 2-3 µm and is very suitable for penetration. [33] reported that Sulfur-containing particles of sizes below 1.5 µm penetrated a office building’s filter unit in ventilation channel easily, elemental removal efficiency of the filter being only 7%. Only a limited number of studies have been carried out on those structures commonly used in buildings. [32] predict, by a simulation model, that penetration through mineral wool insulation is negligible. In reality structures mineral wool insulation is seldom perfectly installed, and timber frame structures are, in respect of particle transport, a combination of cracks, surface contacts, and mineral wool.

Ventilation rate of a building affects indoor particle concentrations, and as the fluxes from indoor to outdoor and outdoor to indoor are typically different, indoor air might become contaminated from other sources than outdoors, such as sources from crawl space or from contaminated building materials. Indoor concentrations are reduced by deposition and increased by re-emission of deposited material. The amount of deposited material depends e.g. on deposition rate, re-emission rate and the cleaning frequency.

Recent studies on particle deposition to indoor surfaces make it clear that the deposition rate varies broadly across conditions. Particle size is undoubtedly important. However, other factors can also influence the deposition rate significantly including interior furnishing (quantity and type of the surface) and the indoor air movement. According to [34] the air movement from zero to 0.142 m/s (which is a typical air velocity indoors) increased the deposition rate by 15% for 1 μm particles and by 24% for 1.9 μm particles. Furnishing had a great impact deposition rate; deposition rate increased over 100% for 1 μm particles at air velocity 0.054 m/s and 78% for 2.5 μm if the empty room was furnished [34]. The highest deposition rates had been reported mainly from field settings [e.g. 30], where the control of experimental settings is limited. Even in the best conditions it is difficult to isolate deposition from the many competing factors that can influence airborne particle concentrations.

In studies [30-32], penetration factors of particles within range of 0.5-2.5 μm have been between 0.5 and 1 depending on the dimensions of studied cracks. These results cover the size distribution of fungal spores; and the peak of spores of 1-2 μm seems to be very capable for penetration if the crack height is higher than 0.1 mm [32]. [32] have estimated that the penetration through mineral wool insulation is negligible. In [16] study mineral wool was inside a real base floor structure, and still the results showed penetration occurred, due to the installation of mineral wool which is seldom perfect allowing some routes for particles. The penetration factors determined by [16] were significantly different than in former studies indicating that surface contacts of mineral wool and other building elements are likely to have important effect on the penetration. The importance of surface contacts seems to be confirmed by tests; e.g. for 1.3 μm particles the penetration factor at 20 Pa was 0.19 when the boards didn’t have any penetration and 0.15 when the four 10 mm holes on the surfaces were open, when the pressure was decreased to 6 Pa the penetration factors were 0.08 and 0.03 respectively. Thus, the holes on the surface boards did not have any effect on the measured penetration of particles but probably the small leakage routes between surface contacts of mineral wool and other building elements.

[35] measured particle and fungal spore penetration through a wooden structure in laboratory. They found out that the penetration was roughly the same within particle size range of 0.6-2.5 μm. The penetration was highly dependant on the pressure difference on the and not that much on the holes in surface boar of the structure (the structure included mineral wool layer under the structure acting as a filter).

Particle emissions from HVAC components

Fibre emission from HVAC components such as round silencers can be remarkable pollutants in the indoor air. In a field study [36] particle emission from HVAC components and occupational exposure were studied in 10 office, school and day care centres. The surface fibre dust density varied in the range of < 0.1 – 4.9 fibres/cm^2 and the accumulation during two weeks period in the range of < 0.1 – 2.6 fibres/cm^2. Fibre concentration in the supply air varied between 0.01-85 fibres/cm^3(fibre length >20 μm). In the study the silencers were also studied in laboratory but no relationship between silencers surface area to the particle emissions could not be generally be drawn but it was feature of different silencer. Detailed results from that study are presented by Kovanen in this Clima2007 congress.

Ventilation rate and VOCs

There are many studies in which the VOC concentrations are evidently lower in buildings with higher ventilation rates. In United States new buildings were measured, built with low-VOC and conventional building products [37]. In that study the air change rate varied between 0.14 to 0.78 ach, TVOC concentrations varying between 1.5 to 2.7 mg/m^3. In a Finnish study by [38] "Allergy House" building with 1.7 ach had the TVOC concentration 10-fold lower than in reference building with 0.8 ach. However, also the materials in allergy building were low emitting, thus, the low concentrations are not only because of higher ventilation rate.

In a recent study by [39] there was not a clear trend showing the concentrations of VOCs being lower in buildings with higher ventilation rate. In the newly finished buildings, the TVOC concentration was significantly lower ($p<0.01$) in the buildings with mechanically supply and exhaust air than in the buildings with mechanical exhaust air. The TVOC and formaldehyde concentrations were also lower ($p<0.01$) in the 6- and 12-month-old buildings with combined mechanical ventilation.

DISCUSSION

Strikingly, there are only a few studies in which the ventilation system of the measured building was mentioned and even less reports of the ventilation rate. However, the ventilation rate and pressure differences as well as leakage routes of the studied building/zone are key factors in understanding the concentrations of impurities in indoor air and their penetration to indoor air. Impurities can arrive indoor air from materials and their surfaces or adjacent zones such as crawl spaces or attics. Also the filters and their contamination and its influence indoors are not well known.

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