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Microbial aerosol filtration: Growth and release of a bacteria–fungi consortium collected by fibrous filters in different operating conditions

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ABSTRACT

Quantitative (CFU counting, ergosterol rate) and qualitative (SEM observations) analyses and a dedicated experimental set-up were combined in this study to examine the growth and release of a bacteria–fungi consortium collected by fibrous filters used in HVAC systems. The influence of three parameters was examined: air relative humidity (60%, 80% or close to 100%), the presence of airflow after microbial contamination of filters, and the nature of the fibrous media (glass or polypropylene fibers).

First, the initial filtration efficiency of the microbial consortium, composed of bacterial cells of *Staphylococcus epidermidis* and fungal spores of *Penicillium oxalicum*, was analyzed and compared to the initial filtration with a polyvinyl-acetate aerosol. Then, microbial behavior was evaluated in terms of microbial growth onto filters (in the situation of a simulated airflow stop) and particles released from filters (after a simulated restart of the ventilation). The results demonstrated that, whatever the operating conditions, *S. epidermidis* did not grow onto filters. On the contrary, *P. oxalicum* demonstrated significant growth multiplying by more than 100 times its number of colonies (CFU) and by more than 10 times its ergosterol rate in saturated moist air conditions. SEM images provided information about microbial behavior. A significant mycelia development was observed after 48 h of filters conditioning at 100% RH, while after a longer period of conditioning (168 h), *P. oxalicum* spores were mostly observed. Regarding particle release, spores were detected downstream of the filters conditioned during 168 h when ventilation was restarted.

1. Introduction

To provide better air quality and comfort to the occupants, many buildings, particularly office buildings, are equipped with HVAC systems to manage the air relative humidity (RH) and temperature (*T*) and to ensure an adequate air exchange. Positive effects of ventilation have been demonstrated (Seppänen & Fisk, 2004): for example, health benefits and better

Abbreviations: AHU, Air Handling Unit; CFU, Colony-Forming Unit; GF, Glass Fibers; HEPA, High Efficiency Particulate Air; HVAC, Heating Ventilation and Air-Conditioning; LOQ, Limit of Quantification; PF, Polypropylene Fibers; PSD, Particle Size Distribution; SEM, Scanning Electron Microscope; TOC, Total Organic Carbon; WHO, World Health Organization

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Nomenclature

B	permeability of the filter (m^2)
d_f	fiber diameter (m)
d_p	particle diameter (m)
RH	relative humidity (%)
T	temperature (°C)
Z	thickness of the filter (m)
ΔP	pressure drop of the filter (Pa)
ΔP_0	initial pressure drop of the filter (Pa)
ε	filter porosity (dimensionless)
μ	dynamic fluid viscosity (Pa s)
v	filtration velocity ($m\ s^{-1}$)

productivity when HVAC is well maintained. Nevertheless, buildings associated with inappropriate ventilation can lead to the occurrence of Sick Building Syndrome (SBS), particularly when bioaerosol concentrations are high (Wålinder et al., 2001). SBS, introduced by the World Health Organization (WHO) in 1983 after complaints of discomfort and particular symptoms from workers, is the most studied pathology in office buildings. The term bioaerosol includes all airborne products of microbial, animal or vegetal origin (Douwes et al., 2003) and can be present in different forms: microorganisms, fragments or compounds of microorganisms, biopolymers and living products (ACGIH, 1999; Xu et al., 2011). The main sources of indoor bioaerosol are outdoor air, occupiers and microbial growth on material (Qian et al., 2012; WHO, 2009).

Indoor air is a specific environment for certain resistant and wild strains of microorganisms (Tringe et al., 2008). Goyer et al. (2001) analyzed 63 work places (36 office buildings, 12 schools and 15 hospitals) during 8 years. Their results demonstrated that the predominant bacterial species were *Bacillus* sp., *Staphylococcus* sp. and *Micrococcus* sp.. Similarly, an analysis of 126 places (47 office buildings, 41 schools, 23 hospitals and 15 factories) showed that the predominant fungal species were *Penicillium* sp., *Aspergillus* sp., and *Cladosporium* sp.. In other studies, *Cladosporium*, *Penicillium*, *Alternaria* and *Aspergillus* were detected in large proportions (up to 90% of the total fungal material) in atmospheric samples (Cooley et al., 1998; El-Morsy, 2006; Fang et al., 2005). The influence of atmospheric conditions (relative humidity, temperature and wind speed) has been demonstrated by Liang et al. (2013) on the fungal spores number concentrations in urban atmosphere.

It has been proved that too much or very long exposure to biological agents, such as microorganisms, in an indoor space can be associated with various health problems for the occupants: infectious diseases, acute toxic effects, allergies, and cancers (Douwes et al., 2003; Knutsen et al., 2012). Moreover, airborne bacteria, fungi and their fragments can reach the respirable size range and penetrate deep into human lungs ($< 10\ \mu m$) (Górny & Dutkiewicz, 2002; Górny et al., 2002; Reponen et al., 2001, 2007). As an example, Jones and Cookson (1983) studied the size distribution of airborne microbiological particles in the ambient outdoor air of a suburban area and showed that 34% of total bacteria and 56 to 96% of fungi could be included in the respirable fraction.

Some components of ventilation systems, such as filters, could represent sources of microbial pollution for indoor air (Bluyssen et al., 2003). HVAC filters capture different kinds of particles, including microorganisms, which could colonize these filters in appropriate humidity and temperature conditions, depending on the HVAC operating conditions (Kelkar et al., 2005; Kemp et al., 1995; Maus et al., 2001; Möritz et al., 2001; Nevalainen, 1993; Price et al., 1994; Simmons and Crow, 1995). The filter medium thus becomes a support for microbial growth. Moreover, HVAC systems are regularly stopped to save energy during long office closures: nights, weekends or holidays. Throughout these periods of ventilation stops, microbial populations collected by the filters are not exposed to airflow and, consequently, the microorganisms are less subject to desiccation phenomena. Thus, if certain conditions occur (such as humidity level, temperature and nutrients), microorganisms can grow significantly during these stops of HVAC systems and fungal spores in particular can germinate and grow (Pasanen, 1998). Possible consequences are the physical release of microorganisms or fragments downstream of the Air Handling Unit (AHU) filters as well as the accelerated clogging of filters or a significant decrease in filter efficiency (Bonnevie Perrier et al., 2008; Jankowska et al., 2000). Antimicrobial agents can inhibit the microbial growth onto filters, as quaternary ammonium phosphate, polyhexamethylene, silver nanoparticles… (Cecchini et al., 2004; Lee et al., 2010). Nevertheless, their use is still uncommon and could promote reactivity with chemical compounds.

This study aimed to investigate the conditions leading to microbial development onto fibrous filters and to microbial release downstream of filters which could decrease indoor air quality. The behavior of a microbial consortium, composed of *Staphylococcus epidermidis* bacterial cells and *Penicillium oxalicum* fungal spores, was analyzed in terms of initial filtration efficiency by fibrous media and after collection by the filters during simulated ventilation stops. Two manufactured media, usually used in HVAC systems, were tested: a Glass Fiber (GF) filter and a synthetic fiber filter composed of Polypropylene Fibers (PF). The influence of three parameters on microbial growth behavior was studied: the Relative Humidity (RH) of the air during the simulated ventilation stops, the nature of the filter material, and the presence/absence of airflow after microbial contamination. For each experiment, microbial release downstream of the filters was measured after a simulated restart of the ventilation.

2. Materials and methods

2.1. Overall methodology

For each set of filters contamination, analyses were carried out in order to estimate the microbial growth or the release potential: one filter for CFU counting, one filter for qualitative analyses by SEM observations and quantification of ergosterol,