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Financial implications of modifications to building filtration systems

James F. Montgomery [a, *], Conor C.O. Reynolds [b], Steven N. Rogak [a], Sheldon I. Green [a]

[a] *Department of Mechanical Engineering, The University of British Columbia, 2054-6250 Applied Science Lane, Vancouver V6T 1Z4, Canada*
[b] *Institute for Resources, Environment, and Sustainability, The University of British Columbia, 2202 Main Mall, Vancouver V6T 1Z4, Canada*

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ABSTRACT

Exposure to airborne particles is a serious health concern worldwide and indoor air quality is a critical factor influencing exposure. This work investigates the impact of modified ventilation and filtration system designs to inform building designers, operators, and policy makers of relative effectiveness and costs. Indoor aerosol dynamics, filter cost, and epidemiological models were combined to compare size-resolved indoor particle concentrations, operation costs, and monetized health benefits to occupants within an office building. System airflow and filter efficiency were modified to compare the relative economic implications. Comparisons were made for a number of cities to examine the impact of variation in local air quality, electricity prices, and economic conditions.

The operation cost of filtration systems was found to vary by a factor of 3 between cities. The monetized health benefits of filter installations outweigh the operation costs by up to a factor of 10. In the majority of scenarios investigated the net benefits of improved filtration were greatest for the highest efficiency filters. Adding or increasing recirculated and return air in the system provides a net financial benefit due to (indirect) societal health benefits outweighing (direct) operational costs for small increases in airflow but has diminishing returns for large increases. Though system changes are economically beneficial from a societal viewpoint, the costs and benefits are borne by disparate parties and policy changes may be required to ensure optimum design and operation.

1. Introduction

Exposure to airborne particles can have detrimental health impacts for human populations [1–7] even for exposure to low concentrations [1,8]. Health impacts associated with exposure to particulate matter (PM) vary widely and include asthma [5], bronchitis [7], cardiovascular disorders [3], lung cancer [4], and premature mortality [1,2,6]. Early studies provided correlations between PM_{10} and health impacts. Recent investigations have shown that the impact is greater for $PM_{2.5}$ and some evidence is emerging that suggests that ultrafine particles (UFP) and the black carbon component of particulate matter have a greater impact on health than do larger particle size fractions [9–11].

A number of organizations have developed air quality guidelines. The World Health Organization (WHO) guidelines for annual average outdoor particle concentrations are 20 $\mu g/m^3$ for PM_{10} and 10 $\mu g/m^3$ for $PM_{2.5}$ [12]. The US Environmental Protection Agency (USEPA) sets similar limits for $PM_{2.5}$ at 12 $\mu g/m^3$. People spend approximately 90% of their time within the indoor environment [13] and as such indoor air quality (IAQ) is important to consider for human health, especially in vulnerable populations. Separate indoor air quality guidelines have not been developed and outdoor concentration limits are often used. Indoor particle concentrations are influenced by both indoor (cooking, smoking, particle resuspension, cleaning activities etc.) and outdoor (atmospheric, industrial, traffic, etc.) sources. The relative contribution of indoor and outdoor sources to indoor particle concentration is a strong function of building type, ventilation system, and particle size. The general trend is one of higher contributions from outdoor sources for small particles with contributions of over 50% for particles smaller than 1 μm [14]. Human exposure to indoor PM is largely controlled by the use of HVAC air filters [15]. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) provides guidelines for air filter use [16] and a method to classify filters, called the Minimum Efficiency Reporting Value (MERV). ASHRAE guidelines recommend that filters with a MERV 6 or higher be installed if the national outdoor air quality standard or guideline is exceeded for PM_{10} or MERV 11 if $PM_{2.5}$ guidelines are exceeded. Filter efficiency guidelines in Europe are dictated based on desired indoor air quality categories set forth in EN15251 [17] but specific desired indoor particle concentrations are not stipulated.

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* Corresponding author. Tel.: +1 604 822 2781.
E-mail address: montgomery@alumni.ubc.ca (J.F. Montgomery).

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Filters are normally specified and sized during the building design and engineering phase based on past experience, rule-of-thumb, or local standards without regard for resulting indoor air quality. The LEED rating system advocates the installation of MERV 13 filters to achieve indoor air quality credits, without specifying an IAQ target or considering the implications of increased energy consumption associated with high efficiency filters. Carlsson and Johnsson [18] have shown that the particle concentration downstream of filters varies by location due to upstream concentration differences and that energy consumption is correlated with filter classification in the European context. Carlsson and Johnsson [18] thus propose that energy consumption could be reduced by selecting filters to meet specific air quality targets. However, they did not provide an analysis of building systems to determine the required filter for specific scenarios.

Filtering the air introduced to the indoor environment can significantly improve occupant health. Modelling efforts have found that the monetized reductions in morbidity and mortality may outweigh the costs of improved filtration by an order of magnitude [19–21]. The efficiency of the filter used has been shown to impact operation cost and IAQ [19,21–23] but the impact of specific MERV has not been investigated. The impact on indoor air quality, system costs and associated financial benefits from improved occupant health as a result of modifications to the filters installed and the system operation is unknown. Additionally, the filtration efficiency required to meet expected air quality guidelines and the cost of operating these systems has not previously been investigated.

The purpose of this study is to develop theoretical models of the financial costs and benefits of HVAC air filtration systems in a number of cities throughout the world representing a broad range of outdoor air quality, electricity prices, and economic indicators (used to scale labour rates, and morbidity and mortality costs). The models will be used to provide insight into the impact of changes to efficiency (MERV) and air handling system operation. Relative impacts of changes to the air flow characteristics such as fraction of recirculated and return air, and the use of increased ventilation rates will be compared based on impacts to system operation cost, indoor air quality, and monetized occupant health outcomes from PM exposure. The results from this work will help to inform industry practitioners and policy makers to understand the impact of system design considerations on occupant exposure to indoor particles, and the potential implications of indoor air quality policies and guidelines. The model developed in this work was implemented as a spreadsheet that is available in the online Supplemental Information; building practitioners can use input parameters appropriate to specific design or policy questions.

2. Model and methodology

Changes in air filtration system parameters will affect the indoor air quality, system operation cost and occupant exposure to airborne particles. To understand the impact on each aspect of the system a number of models have been adapted from previous works and integrated in a novel manner as described below.

A model commercial office building is used to evaluate the impact of modifications to the airflow and filtration system. The office building is assumed to contain an indoor volume of 6,400 m^3 with a floor area of 1,600 m^2 which is typical of the size bin constituting the largest total floor space from the EIA Commercial Buildings Energy Consumption Survey [24]. Occupant density (0.07 people/m^2), and required baseline outdoor air ventilation rate (10L/s/person plus 1L/s/m^2) are determined based on the requirements for IAQ Category A for an open office space [25]. The base model assumes a 100% outdoor air system (other air mixes are also investigated) with flow rate equal to the baseline ventilation rate, an infiltration rate of 0.25ACH [26], and a size resolved (0.001–100 μm) ambient particle concentration to match the annual average PM_{10} and $PM_{2.5}$ concentrations in London, UK [27]. No energy recovery system has been assumed for the model. The building air system is assumed to operate continuously when occupants are present and thermal requirements are met through separate energy control. The air control is assumed to operate with variable fan speed control to maintain constant flow rate throughout operation. The results of this work relate specifically to buildings capable of achieving these controls parameters. The use of alternative base scenarios could provide additional information for specific buildings of interest and can be determined using the model. Outdoor particle concentrations are scaled to match local conditions for comparisons of different cities where indicated. Filter banks are sized in the model to provide a nominal face velocity of 2.5 m/s to match air filter testing specifications [28]. The model assumes a baseline filter bypass of 10% as a representative value. Previous modelling has shown the potential for filter bypass between 1 and 38% for straight, L-shaped, or U-shaped gaps of 1 mm or 10 mm [29]. The impact of filter bypass on results has been investigated further in the Supplemental Information. A schematic of the airflow branches and potential filter locations is shown in Fig. 1.

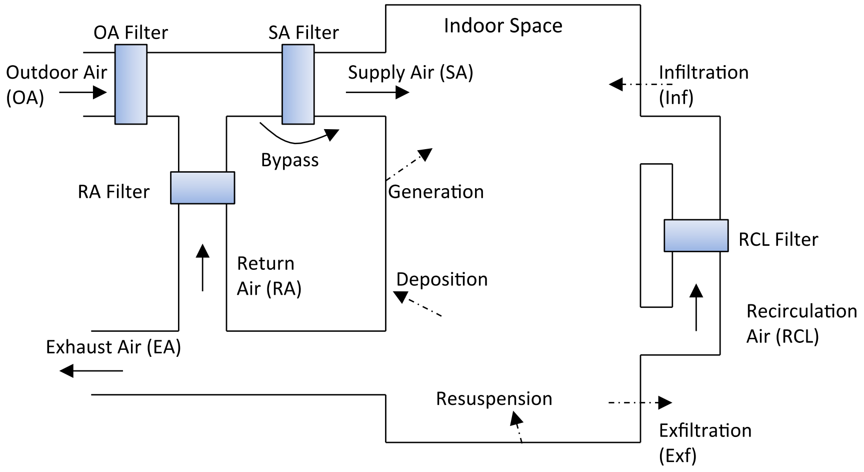

Fig. 1. Schematic of building airflows, potential filter locations, and particle dynamics. A typical building will be designed with one or more of the branches of airflow. Typical filtration systems utilize only a supply air filter while filters are sometimes present in other locations.