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Ventilation effectiveness as an indicator of occupant exposure to particles from indoor sources

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ABSTRACT

Ventilation effectiveness is an indicator of the quality of supply air distribution in ventilated rooms. It is a representation of how well a considered space is ventilated compared to a perfect air mixing condition. Depending on pollutant properties and source position relative to the airflow, ventilation effectiveness can more or less successfully be used as an indicator of air quality and human exposure. This paper presents an experimentally and numerically based study that examines the relationship between ventilation effectiveness and particle concentration in typical indoor environments. The results show that the relationship varies predominantly with airflow pattern and particle properties. Fine particles (1 μm) follow the airflow pattern more strictly than coarse particles (7 μm), and the high ventilation effectiveness indicates better removal of fine particles than coarse particles. When a ventilation system provides high mixing in the space and ventilation effectiveness is close to one, particle sizes and source location have a relatively small effect on particle concentration in the breathing zone. However, when the supply air is short circuited and large stagnation zones exist within the space, the particle concentration in the breathing zone varies with particle size, source location, and airflow pattern. Generally, the results show that for fine particles (1 μm), increase of ventilation effectiveness reduces occupant exposure; while for coarser particles (7 μm), source location and airflow around the pollutant source are the major variables that affect human exposure.

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1. Introduction

Providing an adequate quantity of fresh air to an occupied space is necessary for the dilution of indoor pollutant concentrations [1,2]. However, using building mechanical systems for pollutant dilution is not free. Building mechanical systems use 1/3 to 1/2 of building energy consumption, and a significant portion of this energy is used for conditioning outdoor air [3,4]. Accordingly, increase of the fresh air supply rate, as a single measure that reduces pollutant concentration, does not seem to be an adequate exposure prevention strategy.

Other ways to reduce occupant exposure to indoor airborne pollutants include controlling source emission, cleaning the air, and/or improving ventilation effectiveness. Reduction of source emission and cleaning the air are very effective ways to reduce exposure, but they necessitate the identification of each emitter or the control technology required for each type of source. These requirements are not within the scope of this study. Another alternative is to improve ventilation effectiveness. This can be achieved by: 1) reducing poorly ventilated areas with stagnant air, 2) supplying fresh air to the occupied zones in the space, and 3) effectively removing contaminants before they spread through the space. While the supply flow rate of fresh air per unit space volume, defined as air changes per hour (ACH), represents a quantitative measure of ventilation, ventilation effectiveness is the qualitative counterpart of ventilation system performance. Ventilation effectiveness is a simple air quality indicator that can be used in both the building design phase and for on-site application. As a measure of fresh air distribution in a space, ventilation effectiveness depends on the indoor airflow pattern. Chung and Hsu [5] show that ventilation effectiveness is significantly influenced by the arrangement of inlet and outlet diffusers in the room. The study also showed little correlation between ventilation effectiveness and air exchange rate.

Ventilation effectiveness relates to both the dilution and removal of indoor airborne contaminants as it determines how efficiently supplied fresh air is distributed in the occupied space. Researchers have used several indoor air quality indicators to evaluate the effectiveness of ventilation in relation to pollution control in an occupied space [5–9]. One of the most commonly used indicators in the field is the air-change effectiveness [7,8,10]. This parameter

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describes the quality of supply air distribution in the space, based on the spatial distribution of age-of-air. Age-of-air is defined as the time elapsed from the moment that air enters the space and reaches the considered location. The local value of age-of-air in a specific location describes the freshness of air, and is directly correlated with the airflow path. Air-change effectiveness is defined as the ratio of the age-of-air for perfect mixing to the average age-of-air in a considered zone [10]. Ventilation effectiveness thus characterizes how well the occupied zone is ventilated compared with the perfect mixing condition.

However, ventilation effectiveness does not consider the pollution source position relative to the flow and occupants, and pollutant source location in an occupied space can have noticeable influences on the breathing zone concentration [11]. As a result, previous studies examined the relationship between ventilation effectiveness and occupant exposure with respect to a specific contaminant source position [6,7]. Fisk et al. [6] found a correlation between ventilation effectiveness and the removal of a passive and spatially distributed gaseous pollutant at floor level. Novoselac and Srebric [7] showed variation in the correlation between ventilation effectiveness and the concentrations of gaseous contaminants in the breathing plane for different emission source locations, i.e. occupants, floor materials, and wall paintings. A recent study by Pereira et al. [12] examined particles introduced into a space through various ventilation systems: conventional ceiling, underfloor, and split air distribution systems. The study showed that particle concentration in the breathing zone significantly varies with particle size and arrangement of inlet and outlet diffuser. Taken together, the previous studies in the literature investigated pollutant removal depending on emission source location and ventilation characteristics.

Nevertheless, the majority of previous studies analyzed gaseous types of pollutants which have different dynamics than particulate matter [5–9,11]. Particle transport in a ventilated room is governed by several factors including indoor particle source, infiltration of outdoor particles through ventilation and building envelop, filtration, deposition onto building surfaces, and particle removal by means of ventilation [13]. Particulate pollutants are as common as gaseous pollutants in occupied spaces [14], and sometimes more harmful for health [15]. Even though there have been studies on particle transport associated with indoor airflow distribution [16–21], very few explored the connection between commonly used indoor air quality indicators and the indoor particle distribution.

The aim of this study is to investigate whether ventilation effectiveness can be used as a practical air quality indicator for occupant exposure to particles from indoor sources. The study examines the correlation between the ventilation effectiveness and particle concentration considering a) the whole room and b) the occupant breathing plane, while varying the following parameters: 1) indoor airflow patterns, 2) source location, and 3) particle size. Pereira et al. [12] already analyzed the distribution of particles from various ventilation systems, and therefore this study considers particles from indoor sources.

Since the ventilation effectiveness is typically used in building designs and performance analyses for different ventilation systems, the outcome of this study should help researchers and building designers find when and how much they can rely on ventilation effectiveness as a parameter that reflects the control of particulate pollution from indoor particle sources.

The study is based on a Computational Fluid Dynamics (CFD) analysis validated with experimental measurements. The following sections present the methods used in the study and the results from the parametric analysis. The methods section includes a description of the experimental validation and applied CFD modeling methods, as well as a description of the parametric analysis. The results and discussion section summarizes the validation results, presents the results of the parametric analysis, and discusses the overall findings of the study.

2. Methods

This study applied experimentally validated Computational Fluid Dynamics (CFD) methods and Lagrangian particle tracking simulations to examine airflow distribution and particle transport. Experimental measurements were conducted in a full scale environmental chamber featuring a partitioned office space. This design was chosen given that most office buildings use indoor partitions and has complex multizone airflow through open doors and between partition openings [5,17,18]. The chamber had ventilation systems with a side air supply and exhaust openings and a heated sidewall (window) which simulated typical non-isothermal boundary conditions. In this characteristic environment with supply-jet and buoyancy-driven flow tracer gas decay and particle decay tests were conducted to develop validation data. In the experiments, distributions of age-of-air and particle concentrations were measured along with other airflow parameters and boundary conditions (air speed, surface temperatures, and heat fluxes) needed for the development and testing CFD and particle tracking models. The measured data were used for the selection and adjustment of critical CFD parameters necessary for accurate airflow simulation and indoor particle transport analysis. In the subsequent phase of the study, ventilation effectiveness and particle concentrations were simulated for 54 study cases with different sources and ventilation conditions. The produced data set was used to test if the correlation between ventilation effectiveness and indoor particle concentration in the breathing plane of the room. This correlation was tested for various airflow patterns, number of air changes per hour (ACH), particle sizes, and particle source positions. The correlation data provided the basis to evaluate whether ventilation effectiveness provides information about the magnitude of exposure to indoor particles.

2.1. Validation of CFD and particle tracking models

Fig. 1a presents the experimental set-up for validation of the CFD and particle tracking model. The measurements were conducted in a 5.5 m × 4.5 m × 2.7 m (67 m^3) environmental chamber. A partition wall divided the chamber space into two zones. This partition was introduced to produce internal airflow and particle transport, and the goal was to create large gradients of age-of-air and particle concentrations in the space (Fig. 1b). To achieve this goal, the opening in the partition wall between the two zones was reduced to a smaller area than utilized in typical partitioned spaces. To lower the air mixing in the space, fresh air was supplied at 18 °C into room air at approximately 24 °C using a low-momentum supply diffuser (Fig. 1a). The mean velocity magnitude of the supply air at the 0.53 m × 0.53 m diffuser was 0.1 m/s which provided an air exchange rate of 1.5 h^{-1} and generated a vertical temperature stratification in the space. Furthermore, to generate the airflow typical in a window vicinity, the heated wall in Zone 2 of the test chamber (Fig. 1a) generated a convective heat flux of 320 W, initiating buoyancy-driven airflow near this wall. To measure the age-of-air, a tracer gas decay method was used. Particle distribution measurements were also conducted in conjunction with the decay test. These measurements of temporal and spatial particle concentration distribution in the test chamber provided sufficient data to test and adjust detailed model parameters applied in Lagrangian particle tracking models, which will be described in the CFD and Particle Tracking Simulation Parameters section.