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Particulate concentrations within a reduced-scale room operated at various air exchange rates

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ABSTRACT

Precise prediction of particulate movement is needed to provide a better understanding of how airborne disease organisms move within ventilated facilities. Bacteria often adhere to larger airborne particulates, which will modify their movement behavior in ventilated rooms and may provide an environment to allow them to remain virulent longer. An empty chamber (206 H × 203 W × 386 cm L) with a circular air inlet and outlet on opposite ends was ventilated with air that had a known particulate density. The inlet and outlet openings were sized to maintain inlet and exit velocities at around 5.1 m/s at 5 different air exchange rates (around 2, 4, 5, 9, and 14 air changes per hour – ACH). Particulate concentrations were measured at the air outlet and at 12 locations within the chamber. In this study, the particulate concentration in the inlet air remained constant, so the amount of particulates injected into the chamber increased as the ACH increased. The measured particulate levels at the outlet also increased essentially linearly with an increase in ACH. However, the particulate concentrations in the occupied zone of the chamber did not increase linearly with an increase in actual ACH. Rather, it increased essentially linearly at the lower ACH levels (from around 2 to 5 ACH), but then leveled out at the higher ACH values. The advantages of increasing ACH in terms of providing better environments in the occupied zone of rooms may have limits, which warrant further investigation.

1. Introduction

Maintaining healthy environments in biomedical facilities is a challenging but crucial task. One of the biggest concerns is the transfer of disease organisms within these facilities. This can include transfer of disease between humans in health care facilities or between animals in research facilities. Transmissible airborne organisms are a particular concern because of the difficulty in controlling their movement once they become airborne and follow the air movement within a facility. Adding to these concerns is that these organisms can adhere to particulates and travel with the particulates via air movement [1]·[2]. The particulates may provide micro-environments that allow the organisms to remain virulent for longer periods of time and therefore allow them to infect others at longer distances from the source. Ventilation is the primary strategy for maintaining low levels of airborne organisms within biomedical facilities. There are a variety of mechanisms for ventilation systems to reduce problems with disease transfer, and removing the organisms with the exhaust air is one important means.

However, conditioning ventilation air is very expensive and consumes a large amount of energy. Conditioned ventilation air can cost around $8/cfm/yr which is a substantial cost for large biomedical facilities that have high air exchange rates to maintain healthy environments [3]. Increasing the air exchange rate of a typical 70 m^2 laboratory from 6 ACH to 14 ACH would increase the annual HVAC energy cost by around $5000 [3]. The air exchange requirements specified in the *Guidelines for Design and Construction of Hospital and Health Care Facilities* [4] vary by the room use, but many rooms in human health care facilities require between 6 and 15 total air changes per hour (ACH). The *Guide for the Care and Use of Laboratory Animals* [5] specifies 10–15 fresh ACH in animal rooms to maintain macro-environment air quality. It is important to provide the correct amount of ventilation air to reduce transmissible airborne organisms, but over-ventilation leads to unnecessary use of energy with the resulting high costs and environmental problems such as the release of greenhouse gases and pollution.

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In order for ventilation needs to be determined more precisely, there is need for a better understanding of how airborne organisms move within ventilated facilities. Most bacteria are relatively small (0.3 to over 20 μm [6]) and most tend to follow air movement closely due to low gravitational and inertial effects. However, if bacteria adhere to larger airborne particulates, the larger aerodynamic diameter will give them a different movement behavior in ventilated rooms. In addition, the particles may provide a protective environment that could allow the bacteria to remain virulent longer thus allowing them to remain virulent for a longer distance. Memarzadeh and Xu [7] report that it is important to understand the role that particle size and particle transmission plays in infectious disease transmission. Respiratory droplets carrying infectious pathogens will transmit infection when they travel directly from the respiratory tract of an infected person to the mucosal surfaces of a susceptible recipient [7]. Pathogen laden droplets are expelled into air by an infected person by coughing, sneezing, breathing and talking [8]. A sneeze can produce numerous large droplets that may initially be up to 20 μm [7–9]. Larger particles are more influenced by inertia and gravity forces and are less likely to be removed quickly from the path towards potential recipients by room air movement. Consequently, it is important to better understand the impact of room air flow on the path of larger particles.

Increasing air exchange rates has often been used as a means to remove airborne pathogens from occupied zones. Of primary interest is the impact of increasing air exchange levels on the particulate concentrations in the occupied zone. The occupied zone would be the area in a room that would normally be occupied by people or animals. In facilities where health is a concern, the general guidance is that more air exchange is better because it will reduce concentrations of contaminants such as gases, particulates and disease organisms. Predicting disease transmission via airborne organisms is more difficult than predicting something like the reduction of gas concentration with ventilation. It may only takes a few organisms to infect a susceptible recipient, so all areas need to be adequately ventilated to quickly remove pathogen laden particles from occupied areas of the room. Increasing the air exchange rate alone does not guarantee sufficient control of the transfer of airborne infection everywhere within a room. The entire ventilation system needs to be analyzed to determine the likely path of pathogen laden particulates within the occupied zone of rooms.

Computational fluid dynamics (CFD) is a powerful tool for predicting air movement within ventilated spaces along with the resulting movement of particulates. There are a variety of factors important in modeling particulate movement which were discussed by Memarzadeh and Jiang [10]. Empirical data help to make CFD more accurate by providing boundary conditions for setting up the model and providing results for validating the results of modeling. Empirical results also provide good direction for future research. Of particular interest along the lines of this discussion, is to initially obtain empirical results on the effects of various total air exchange rates on particulate movement within a simple (empty) ventilated space. Injecting ventilation air with a known particulate density and measuring particulate concentrations at the air outlet and within the area normally occupied in the room should provide data on particulate movement and adherence to room surfaces.

The objectives of this study were to empirically determine the effect of various total air changes per hour on particulate concentrations in the occupied zone and ventilation outlet of an empty ventilated chamber given a known particulate density within the incoming ventilation air.

2. Materials and methods

2.1. Particulate test chamber

A particulate test chamber (PTC) (inside dimensions of 206 H × 203 W × 386 cm L) with a wood frame and plywood inner liner was constructed (Fig. 1). The inner surface of the chamber was coated with a smooth, non-electrostatic paint that was grounded. There is one entry door on the inlet endwall which closes tight to form a seal around the perimeter. An air inlet was centered in the width of one end and is centered 153 cm above the floor surface. An air outlet was placed in the opposite end at the same location. The inlet and outlet openings are circular, interchangeable tubing that were sized to maintain inlet and exit velocities at around 5.1 m/s at the desired air exchange rate (Air Changes per Hour – ACH) values (4.75 cm inside diameter for 2 ACH; 6.71 for 4; 8.20 for 6; 9.47 for 6; and 11.61 for 12. The inlets were stainless steel tubing sections (Fig. 2) that were 15 cm long, and the inside diameter varied to provide the desired air velocity entering the PTC. These seamless inlets were made from food-grade stainless steel, and the tubing diameter was fabricated within ±0.0025 cm of the specified diameter. When developing this chamber, it was assumed that the round inlet with no obstruction would provide relatively low turbulence. In addition, we intended to create a relatively high turbulence in the round inlet by placing a smooth rod in the center of the round opening, several inches back from the interior surface of the outlet within the PTC. The tests run with no rod in the inlet were designated as “N”. The test runs conducted with the turbulence rod in the inlet were designated as “T”. The diameter of the turbulence bar and placement back from the interior wall edge varied with the ACH value. For 2 ACH, the bar diameter was 0.48 cm and it was placed 25.4 cm back from the interior surface; for 4 ACH – these dimensions were 0.79 cm and 26.7 cm; for 6 ACH – 0.148 cm and 27.9 cm; for 8 ACH 1.27 cm and 27.9 cm; and for 12 ACH – 1.59 cm and 127.9 cm. Interior temperatures and relative humidities within the PTC were measured with an Omega (Model HX94C) transducer placed in the center of the room volume.

2.2. Air inlet system

Inlet air was drawn through a 3.8 cm diameter PVC pipe from an air-conditioned room (approximately 21 °C) by two centrifugal fans. The fans pushed the air through an electronic valve (Dwyer Instruments, Model PBVPV1206) to control airflow. The air then

Fig. 1. Side view of particulate test chamber (PTC).