Building and Environment 92 (2015) 246-255

Contents lists available at ScienceDirect

Building and Environment

Journal homepage: www.elsevier.com/locate/buildenv

Effects of air exchange rate, particle size and injection place on particle concentrations within a reduced-scale room

W. Brock Faulkner [a], Farhad Memarzadeh [b], Gerald Riskowski [a,*], Ahmad Kalbasi [a,c], Audrey Ching-Zu Chang [d]

[a] Texas A&M University, Biological and Agricultural Engineering Dept., College Station, TX, USA
b National Institutes of Health, Division of Technical Resources, Bethesda, MD, USA
c Food Engineering at University of Tehran, Karaj, Iran
d National I-Lan University, Food Science Dept., I-Lan, Taiwan

ARTICLE INFO

Article history:
Received 3 November 2014
Received in revised form
28 April 2015
Accepted 29 April 2015
Available online 9 May 2015

Keywords:
Airborne disease transmission
Particulate concentrations
Air exchange
Aerobiology
Chamber measurements

ABSTRACT

Using aerobiology and engineering strategies to study particle movement in ventilated rooms is a powerful tool for understanding airborne disease transmission in healthcare facilities. More research is needed on movement of particles in ventilated rooms and more empirical data is needed to show effects of air exchange rates on particulate movement within a simple ventilated space. Results from this study can provide data for more complex strategies like Computational Fluid Dynamics (CFD) to help design ventilation systems in healthcare facilities where airborne disease transmission is a concern. In this study, particles were injected into a reduced-scale chamber to measure particle mass concentrations at twelve locations throughout the ventilated space and at the ventilation exhaust. Experiments had three particle sizes (1.9, 5.4, and 7.9 μm) of borosilicate glass, five levels of ventilation rate (nominally 2, 4, 6, 8 and 12 air changes per hour), and two injection locations (center and side). The ventilation system had one round inlet centered in one wall at ¾ height and one outlet in the opposite wall. Three replications were conducted for each combination of variables for a total of 90 tests. Increasing ventilation rates reduced concentrations of 1.9 μm particles in the occupied zone but had little effect on room concentrations of 5.4 and 7.9 μm particles. Exit concentrations for 1.9 μm particles were higher than for 5.4 and 7.9 μm particles. For 1.9 μm particles, average concentrations decreased linearly with increasing ventilation, while similar trends were not seen for the larger particles.

1. Introduction

Mitigating transfer of disease organisms is a primary design consideration for biomedical and healthcare facilities. Once these organisms become airborne, they are difficult to control and they follow the movement of air within a facility, or they adhere to particles and travel with them in the air [1,2]. Ventilation is the primary strategy for maintaining low levels of airborne organisms within biomedical facilities. The ventilation system should provide sufficient air to reduce or remove transmissible airborne organisms, but over-ventilation leads to unnecessary costs. Conditioning ventilation air is expensive and consumes energy. Conditioned ventilation air can cost around $8/cfm/yr [3] and biomedical facilities have high air exchange rates to maintain healthy environments. The *Guidelines for Design and Construction of Hospital and Health Care Facilities* [4] specifies air exchange requirements for various healthcare functions and many types of rooms in healthcare facilities require between 6 and 15 total air changes per hour (ACH). The *Guide for the Care and Use of Laboratory Animals* [5] requires 10-15 fresh ACH in research animal rooms.

Ventilation system engineers need a better understanding of how airborne organisms move within ventilated rooms in order to design ventilation systems for healthcare facilities that are more effective and cost efficient in reducing or removing transmissible infectious organisms via the airborne route. Bacteria are small (0.3 to over 20 μm [6]) and tend to follow air movement closely due to low gravitational and inertial effects. The size of *Mycobacterium tuberculosis* airborne particles are 1-5 μm [7]. One of the most studied airborne infectious bacteria is *M. tuberculosis*, which is

* Corresponding author. 2117 TAMU, Texas A&M University, College Station, TX, USA. Tel.: þ1 979 845 7619; fax: þ1 979 847 8627.
E-mail address: Riskowski@tamu.edu (G. Riskowski).

http://dx.doi.org/10.1016/j.buildenv.2015.04.034
0360-1323/

carried in airborne particles called droplet nuclei. Droplet nuclei are small airborne particles that remain after the desiccation of large droplets [8] generated when infected persons cough, sneeze, talk, or sing. The size of *M. tuberculosis* airborne particles are 1-5 μm [7] and they are carried by normal air currents that can keep them opposite ends that was ventilated with air that had a airborne for prolonged periods, thereby spreading them throughout a wider area.

The ASHRAE Position Document on Airborne Infectious Diseases stated that the primary concern is with person-to-person transmission of infectious disease by small airborne particles that contain microorganisms [7]. Small particles can stay airborne for long periods of time and can be transported relatively long distances, whereas, large droplets generated by an infected person are relatively heavy and settle to surfaces about 1 m from the source. Thus, HVAC systems can influence the movement of small particles but have a smaller effect on the movement of large droplets. The dividing line between the size of small airborne particles and droplets is a matter of debate, but generally if the particles or droplet nuclei is ≤10 MMAD (mass median aerodynamic diameter), they would be within the category of a small particle and would generally remain airborne [7]. Memarzadeh and Xu [9] stated the importance of understanding the role that particle size plays in the transmission of infectious organisms. Respiratory droplets can carry pathogens from the respiratory tract of an infected person to the mucosal surfaces of a recipient [9]. Droplets are expelled into the air by an infected person by coughing, sneezing, breathing and talking [10]. A sneeze can produce numerous large droplets that may initially be up to 20 μm [9-11]. Consequently, it is important to better understand the impact of room airflow on the path of various sizes of particles.

Studies show that ventilation systems may affect indoor disease transmission [12] [13]. One review paper reported that airflow patterns directly contribute to the airborne spread of infectious pathogens [14]. Others have shown that airflow rates can influence the transport and removal of human expiratory droplets [15-17]. Further studies have shown that the transport and removal of human expiratory droplets were size specific and the effect of ventilation airflow on particle fate varied with droplet size [18-20]. The impact of the different droplet removal mechanisms varied with droplet size. Research has shown that room airflow patterns have a significant impact on control of infectious disease organisms because most of these organisms are introduced into the room by occupants or objects within the room [21]. It was found that droplets from coughing and sneezing can travel 3 m, and the exhaled droplets are in polydisperse form [22].

The primary strategy for reducing airborne pathogens from occupied zones is to use high air exchange rates, which is costly. The occupied zone is the area in a room that would normally be occupied by people or animals. In health facilities, the general guidance is that more air exchange is better because it will reduce concentrations of contaminants such as disease organisms. Predicting disease transmission via airborne organisms is more difficult than predicting something like the reduction of gas concentration with ventilation. It only takes a few viable organisms to infect a susceptible recipient; so all areas of the room 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.

One way to achieve this is to observe particle movement under specified controlled conditions. A recent study was conducted to measure particulate concentrations in an empty chamber (206 H × 203 W × 386 L cm) with a circular air inlet and outlet on known particulate density [23]. The inlet and outlet openings were sized to maintain inlet and exit velocities at around 5.1 m s^{-1} 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. This study indicates that in some situations there may be limits to the advantages of increasing ACH in terms of providing better environments in the occupied zones of rooms, which warrants further investigation given the fact that increasing ACH greatly increases energy consumption and cost.

Empirical data is useful for Computational Fluid Dynamics (CFD) modeling of air and particulate movement in health facilities. Computational fluid dynamic models are less expensive to conduct than full scale experimentation [24]. Consequently, as CFD has become more available and more sophisticated, it has been used to predict room air movement in various types of healthcare settings [25]. As with CFD models for other types of facilities, few have been validated with experimental data [22]. Empirical data helps to make CFD more accurate by providing boundary conditions for setting up the model and providing results for validating the results of modeling. There are a variety of factors important in modeling particulate movement which were discussed by Memarzadeh and Jiang [26]. To predict the movement of these particles, the effects of ventilation system design parameters and particle characteristics on particle movement should be studied [27].

Ventilation strategies for hospital rooms are complex because of the need to prevent cross-contamination from a source to a recipient. The ability of a ventilation system to control levels of particulate contaminants within a room depends on a number of factors beyond just the air exchange rate. Among these factors are particle origin, size, composition, and type, temperature and humidity, the duration that particles can remain airborne, and the distance that particles can travel. Air in ventilated rooms is not perfectly mixed especially from the perspective of larger particles. The concentration of pathogen laden particulates at any given location and point in time depends on the location of the source, the local airflow patterns, disturbances and obstructions in the room, and the particles on which the pathogens are carried.

The criteria that define airborne transmission of a disease include dissemination via air currents of either airborne droplet nuclei or small particles that can be inhaled by a susceptible recipient and that remain infective over time and distance. The infective source may or may not be in the same room as the susceptible recipient [28-31]. Specially designed ventilation systems are used to remove or dilute infectious particles [32,33]. Airborne infectious agents include *M. tuberculosis,* rubeola virus (measles), varicella-zoster virus (chickenpox), and spores of Aspergillus spp.

Neither the US or UK specify airflow patterns within hospital rooms and assume that dilution ventilation will be used [34]. CDC guidelines [33] had advocated downward airflow systems in hopes that gaseous or small particulate contaminants move downwards towards vents before they were mixed within the occupied zone air. The 1999 ASHRAE Handbook-Applications [35] suggests that to reduce cross-contamination in operating rooms “the delivery of air from the ceiling with a downward movement to several exhaust

inlets located on opposite walls, is probably the most effective air movement patter for maintain the concentration at an acceptable level." Although sparse, there have been some studies related to ventilation of hospital rooms.

Beggs et al. [34] used CFD to simulate three different ventilation strategies in an empty hospital room using simulated particles. The ventilation strategies simulated 1) a low air supply in one wall with a high air exhaust in the opposite wall, 2) a high air supply in one wall with a low air exhaust in the opposite wall and, 3) an air supply in one end of the ceiling with an air exhaust at the other end of the ceiling. The simulated particles were small enough to follow airflow patterns from a source in the center of the room and the average contaminant concentration in the entire room was calculated. The air exchange rate was 6 ACH. They found that Strategies 1 and 2 had much higher (4-5 times higher) room concentrations than did Strategy 3. Moving air across the rooms with wall mounted diffusers had much higher contaminant concentrations than moving air from a ceiling inlet to a ceiling exhaust. The modeled contaminant concentration movement plots indicated that with Strategy 3, the contaminants were picked up by the air as it moved down from the inlet and carried the contaminants to the exhaust with less mixing than did the cross flow patterns generated by Strategies 1 and 2.

Zhang and Chen [36] conducted CFD modeling of rooms with three types of ventilation systems: 1) ceiling air supply and sidewall exhaust (dilution ventilation at 43 ACH), 2) sidewall supply and exhaust (dilution ventilation at 22 ACH) and, 3) underfloor air distribution (UFAD) (displacement ventilation at 7 ACH). They used empirical data from Murakami [37] (particle sizes 0.31 μm for System 1 and 0.31, 1, and 4.5 μm for System 2) to validate systems 1 and 2, and new experiments were conducted to obtain data for the UFAD system (particle size 0.7 μm). Zhang and Chen [36] concluded that airflow patterns have a significant impact on the particle concentration distribution in rooms. Although they did not consider the deposition rate of particles within the room in their study, they found the UFAD had the best particle removal efficiency. However, they expressed concerns about particle resuspension from foot traffic.

Qian et al. [12] studied mock hospital rooms using N_2O tracer gas as a model for movement of microorganisms. They tested the personal exposure of people in the room by using breathing mannequins as simulated patients in beds with 3 different types of ventilation systems - mixing, downward airflow, and displacement ventilation. The air exchange rate was 4 ACH. They found that contaminants from a source patient could be well mixed by ambient air in mixing and downward airflow ventilations systems. However, the downward ventilations systems combined with the exhalation jets of the patients led to pollutants being mixed into the occupied zone. On the other hand, these systems diluted the contaminant concentration of the patient exhalation jet more quickly than in the displacement ventilation system which had much slower movement of air within the occupied zone. For displacement ventilation, care needed to be taken to keep the more polluted upper stratification layer above the breathing zone of standing occupants. Exhalation jets from patients, thermal plumes from occupants and disruption to airflow from moving occupants and static obstructions can overcome ventilation strategies that hope to stratify pollutant levels within the room and thus reduce exposure levels within the occupied zone.

Cheong and Phua [38] used CFD to study 3 different ventilation strategies in hospital isolation rooms. Strategy 1 involved air supply diffusers in the ceiling at the center of the room width and exhaust grilles in the ceiling near one wall of the room. To provide data to help validate their CFD model, they also physically tested Strategy 1 at full scale with a tracer gas as the contaminant from a simulated patient in a bed position. Air exchange rate was very high at 30 ACH. They also modeled airflow entering the room under the entry door. Strategy 2 involved air supply diffusers in the ceiling at the center of the room width and exhaust grilles in one wall near the floor of the hospital room. Strategy 3 involved air supply grilles in the ceiling near one wall and exhaust grilles in the nearby wall near the floor. They assessed their ventilation system effectiveness in terms of contaminant concentration within the breathing zone of a healthcare worker in the room. The data demonstrated that Strategy 1 had the highest concentration of contaminants in the occupied zone. The high ACH value (30) used in this study would have led to high velocities and high mixing within the room. Strategy 2 had contaminant levels in the occupied zone that were about half that of Strategy 1. Strategy 3 was slightly lower contaminant levels than Strategy 2. Cheong and Phua [38] concluded that air supplies and exhaust grilles should be arranged to allow clean supply air to flow from the clean healthcare provider breathing zone towards the most contaminated zone near the patient breathing zone. However, they did not simulate the effects of factors that may disrupt ventilation airflow or release contaminants from other sources such as bedding.

More research is needed to better understand the movement of particles in ventilated rooms. 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. The movement of various ranges of polydisperse particles that are injected at different locations within the room are of special interest because they simulate particles that might be expelled in a healthcare facility from an infected person by talking, breathing, coughing or sneezing. Analysis of the movement and concentration of these particles injected and extracted from a specified location and at specific ACH may help us better understand how to optimize ACH and inlet and outlet parameters of an HVAC system in a healthcare facility. Injecting known levels of particulates and measuring particulate concentrations at the air outlet and within the area normally occupied in the room should provide data on particulate movement within a ventilated room.

Various researchers have focused on the ventilation and deposition of wide ranges of micro particles rather than particles of a specific size. For example, particles with the range of D = 0.1-200 μm [39], aerosol or ultrafine particles (D = 0.1-400 nm) in the outdoor and indoor facilities [40,41], biological aerosols (D = 0.54-6.24 μm) such as fungal spores [42], and chemical particles (D = 0.5-1.0 μm) which are artificially generated [43]. Much less attention has been focused to the concentration of exhaled particles with sizes from 1 to 8 μm, which are generated during breathing, speaking and coughing in indoor facilities [44].

Engineering studies of particle movement in a ventilated room are very useful tools for understanding airborne disease transmission in healthcare facilities. The objectives of the proposed study are 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 reduced-scale chamber given a known particulate load within the chamber. The objectives include the effect of three sizes of particles injected at two locations in the room.

2. *Materials and methods*

2.1. *Particulate test chamber*

PM concentrations were measured in a confined and sealed particulate test chamber (PTC) with inside dimensions of 206 cm (H) × 203 cm (W) × 386 cm (L). A schematic of this experimental

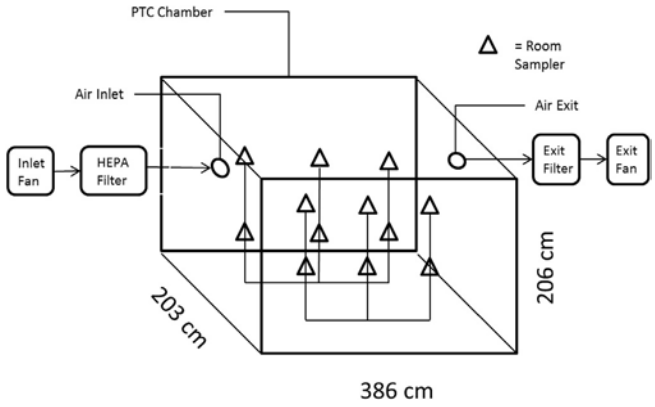


Fig. 1. Schematic of the particle test chamber layout.

system is shown in Fig. 1. The PTC was of wood construction, and the interior surface was painted with a smooth and grounded non-electrostatic paint to minimize the friction velocity and electrostatic forces in this study. Unsmooth and rough wall surfaces in the indoor buildings may lead to more particle deposition when the dispersed particles have 1-10 mm diameters [45]. Stainless steel circular inlets and outlets of varying sizes (made by Kurt J. Lesker, Inc., PA) were centered in the narrow walls and 153 cm above the floor surface and sized to provide nominal ventilation rates of 2, 4, 6, 8, and 12 air changes per hour (ACH) and maintain air velocity at both the inlet and outlet of approximately 5 m s^{-1} (Fig. 2). Two centrifugal fans equipped with variable speed motors moved cooled air (21 °C) through an electronic valve (Dwyer Instruments, Model PBVPV1206) to conduct and control airflow through a PVC pipe duct (D = 3.8 cm) on the inlet side of the room. This airflowed through a HEPA filter to remove particles and a precision airflow nozzle [46] to measure airflow before entering the PTC as inlet air. Feedback from the precision nozzle was used to control airflow through the PTC. The precision nozzles had a 2.5 cm orifice diameter for the 2 and 4 ACH runs and a 5 cm orifice diameter for the 6, 8, and 12 ACH tests. Pressure drop across the precision nozzle was measured with a differential pressure transducer (Dwyer Instruments; Part number 677-7). A vacuum blower was placed downstream of the exit filter to draw air from the PTC and through a stainless steel pipe (26.7 cm long) and then through an outlet with glass fiber filter (Type A/D-66227, Pall Corporation, Ann Arbor, MI). The outlet pipe inside diameter varied with airflow to match the inlet diameters. For a given test, inlet and outlet fan speeds were adjusted using LabView (Version 8.0, National Instruments Corporation, Austin, Texas) to maintain the desired ventilation rate through the PTC while also maintaining a negative pressure (-0.50 inches of water or 25.5 Pa) in the chamber. Filter sizes for the air outlet were dependent on the airflow rate - 6.35 × 10.16 cm for 2 ACH, 10.16 × 12.7 cm for 4 and 6 ACH, 12.7 × 20.32 cm for 8 and 12 ACH.

2.2. *Air exchange rate and turbulence intensity tests*

The air velocity and turbulence intensity of air entering the PTC was determined at the inlet for each air exchange rate. The ventilation system was allowed to run for 10e15 min to reach the target set points and stabilize. A hotwire anemometer system (IFA 300 with Model 1210 Probe; TSI Inc., Shoreview, MN) equipped with a Positioning Slide Traverse was used at the PTC air inlet to record the required data at constant temperature. Velocity was measured at different points along the horizontal and vertical axes of the inlet opening diameter in 10 mm sequential increments for each air inlet, and the process was repeated three times. The air exchange rates were calculated from the measured air velocity and the known inlet diameter and chamber dimensions. Turbulence intensity was calculated from Equation (1).

Fig. 2. Front view of testing chamber with air inlet pipe (top). The outlet system in the back view (bottom) contains a glass fiber filter and connects to a vacuum pump.

$$T.I. = (SD/U)*100\% \quad (1)$$

where T.I. = turbulence intensity e one dimensional, SD = Standard deviation of velocity readings, and U = average of velocity readings.

2.3. *Particle injection*

Three sizes (1.9 μm, SD = 0.6 μm; 5.4 μm, SD = 0.7 μm; and 7.9 μm, SD =1.0 μm) of standardized borosilicate glass beads (Duke Standards, Thermo Scientific, Fremont, CA) with density of 2.5 g cm^{-3} were used. The particle mean diameters for the particles used were traceable to NIST, and they have high mechanical and thermal stability [47]. These particle sizes are within the mid-range of sizes for bacteria [6] and are within the mid-range of human expired droplets [10] as were discussed earlier. For a given test, 0.32 g of certified particles was weighed and added to 10 mL of a solvent containing 70% ethanol and 30% deionized water (which contained 0.2% xanthan gum). The resulting solution was heated and agitated using an Ultra Sonic Mixer (Model 08890-01; Cole-Parmer Instruments Co., Verona Hills, IL) for at least 10 min to suspend the particulates in the solution.

The solution was then transferred to a jet nebulizer and weighed with an electronic balance having precision level of 0.1 mg (Model MS104S/03, Mettler Toledo International Inc., Schwerzenbach, Switzerland). The jet nebulizer (Fig. 3 - top; Pari Model, Hugo Sachs Electronik-Harvard Apparatus GmbH, March-Hugstetten, Germany) was used to inject the combination of pressurized air (1.5 atm), solvent, and particulates vertically upward at low velocity (~1 cm s^{-1} or 0.6 m min^{-1}) and nominal mass flow rate that averaged 278 (SD = 39) mg h^{-1}. For a given test, particles were injected in one of two locations, either 84 cm (side) or 102 cm (middle) from the longer wall. Both injection locations were 193 cm from the end wall and 79 cm above the floor.

The particles were stable glass beads so they would not change size. The chamber air had relative humidity that typically ranged from 30% to 50%, so it would not be anticipated that the particles would increase in size in the chamber due to water accumulation from the air. Most of the droplets from a nebulizer would be in the 0.3-10 μm range [48]. Water droplets of 10 ṁm would evaporate in 0.6 s at 20 °C and 80% relative humidity [48] and in 0.08 s at 0% relative humidity [49]. Our solution was 70% ethyl alcohol and a 10 μm droplet of ethyl alcohol would evaporate in 0.03 s at 20 °C and 0% relative humidity [49]. Consequently, the nebulized droplets or liquid films on the glass beads would evaporate very quickly to leave only the glass beads in the air within a very short distance from the nebulizer. There could be some potential for coagulation of the glass beads to form larger particles. Adhesive forces for particles include electrostatic force and liquid film. We already discussed why liquid films would quickly evaporate in this situation. Van der Waals force has little influence beyond a few molecular diameters distance between surfaces [49]. The number of particles injected into the chamber over each 30 min test run was relatively low and the particle density would be relatively low, so there would be relatively few particle collisions at this low density.

Fig. 3. The nebulizer (top) and air samplers (bottom) installed in the testing chamber to suspend the particles and collect them, respectively.

Therefore, it is not expected that coagulation of particles would be a major occurrence in this system. We placed glass slides in the chamber to collect the glass particles during test runs. The slides were placed 30 cm away and 15 cm below the nebulizer during test runs. The collected glass particles were observed with a Nikon Eclipse TS100 microscope. Our observations found that fewer than 2.5% if the particles may have been pairs and the remainder were individual particles. However, the number of possible pairs may be overstated if particles observed on the slide were deposited near each other but at different times.

2.4. Particulate sampling system

Concentrations within the room were measured at 12 locations using low volume total suspended particulate (TSP) samplers (Fig. 3 - bottom; as described by Wanjura et al. [50] and Faulkner et al. [23]. Table 1 shows the locations of samplers within the chamber. These samplers measured total suspended particulate mass concentration per unit volume of air (μgm^{-3}). Concentrations within the room were measured using PTFE (Polytetrafluoroethylene) filters (47 mm diameter supported with a polypropylene ring), which were conditioned in a desiccator at room temperature for 24 h and then weighed three times using an analytical balance (Mettler Toledo, Model XP205) with ±10 μg precision. When the standard deviation (SD) of the three weights of each filter was less than 50 μg, the average weight was recorded and used for data analysis. Otherwise, the weighing of each filter was repeated until the SD of three weights became less than 50 μg. A similar procedure was used to condition and weigh filters after they were loaded with particulates.

2.5. Experimental procedure

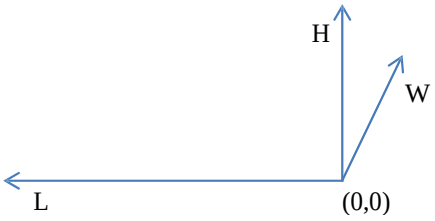
In order to stabilize the airflow patterns in the PTC, the ventilation system was allowed to operate for at least 15 min prior to initiating particulate injection. Then the 12 circulating air pumps (installed outside the PTC and connected to the 12 room air samplers) were started after initial pressure adjustment to suspend particulates inside the chamber (Fig. 4). The air samplers and nebulizer were turned on simultaneously to avoid sampling clean air that would bias the concentration data. Each sampler operated at a flow rate of 16.7 L min^{-1}, and sampled air was recycled back into the room through a PVC pipe (D = 10 cm) at an inlet velocity of ~0.4 m s^{-1} in the lower section of one sidewall near the outlet of the PTC. Sampler flow rates were monitored using calibrated sharp-edged orifice meters. A pressure transducer was used to measure the pressure drop across the orifice meter, and HOBO data-loggers were used to record pressure drop values every 2 s throughout each test. The LabView program was used to adjust the ventilation system based on continuous reading of the static pressure across the precision nozzle in the inlet air duct along with barometric pressure, temperature, and relative humidity measured using an Omega (Model HX94C) transducer placed near the center of the room volume. The sampling portion of each test operated approximately 30 min. At the conclusion of a given test, the 12 in-room samplers and particle injection system were turned off, and then the ventilation system was turned off. Upon the conclusion of the test, filters were collected and the room walls and floor were vacuumed with an industrial vacuum with a HEPA filter to remove any deposited particles and setup for the next test.

2.6. Statistical analysis

Experiments were conducted according to a randomized complete block design (blocked by replication) with three replications

Table 1
Locations of 12 room air samplers in the PTC. The lower, left hand corner of the inlet end wall of the chamber was considered the origin. The X, Y and Z axes run respectively along length (L), width (W), and height (H) of the chamber.

Sampler	A cm	B cm	C cm	D cm	E cm	F cm	G cm	H cm	I cm	J cm	K cm	L cm	Inlet cm	Outlet cm
L (X-coordinate)	95	95	95	95	191	191	191	191	288	288	288	288	0	386
W (Y-coordinate)	67	67	135	135	67	67	135	135	67	67	136	136	102	102
H (Z-coordinate)	138	72	138	72	138	72	138	72	138	72	138	72	153	153



for each treatment for a total of 90 tests (ventilation rate (5) × particle size (3) × injection location (2)). Analysis of variance (ANOVA) tests were conducted using Design Expert software (v. 9; Stat-Ease Inc.), and a hierarchal model was specified.

In order to satisfy the assumptions required for ANOVA, a square root transformation was applied to concentration measurements before analysis, and two outliers were removed from the dataset. Both outliers were more than three standard deviations higher than the mean concentration for that treatment and were from the sampler closest to the injection point for 2 ACH treatments with 1.9 ㎜ particle size. It is likely that, at such low ventilation rates, many of the injected particles did not disperse well, leading to higher-than-expected and non-representative concentrations at the nearest sampler.

After pre-processing the data, an ANOVA was conducted with the square root of concentration as the response variable and the following fixed factors: injection location, ventilation rate, particle size, sampler elevation, sampler distance from inlet Table 2. Four potential covariates were identified (inlet velocity, ventilation system flow rate, mass of PM dispersed, and sampler code). The first three were auto-correlated with one or more fixed factors and were, therefore, not included in the analysis. Factors that were not significant at the p = 0.10 level were not included, nor were their interactions. Interactions included were injection location x particle size and ventilation rate x particle size. The observed power of all statistical tests was greater than 0.85.

Table 2
Results of ANOVA.

Factor	p-value	Deg. freedom
Injection location	<0.0001	1
Ventilation rate	<0.0001	4
Particle size	<0.0001	2
Injection location × particle size	0.0053	2
Ventilation rate × particle size	<0.0001	8

3. *Results and discussion*

3.1. *Particulate concentration results*

Room particulate concentrations did not vary by sampler code, sampler elevation, or distance from the inlet, indicating that concentrations within the PTC were relatively uniform. Location of the ventilation inlet and outlet at opposite ends of the chamber may have resulted in such uniformity. There was no significant difference between the concentrations of the similarly-sized particles at 1/3 the chamber height (near the floor) and 2/3 the total chamber height, regardless of ventilation rate or injection location.

The effects of ventilation rate (across particle sizes and injection places) on PM concentrations within the PTC and at the exit are shown in Fig. 5. Within-room concentrations decreased linearly with increasing ventilation rates, while the exit concentrations

Fig. 4. General view of the 12 circulating air pumps that were connected to the 12 room air samplers. The air pumps were installed outside the PTC.

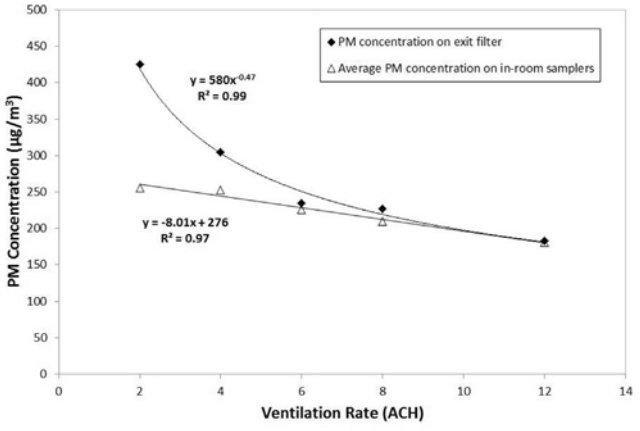


Fig. 5. Effects of ventilation rate on PM concentrations within the PTC and at the exit filter across all particle sizes and injection locations.

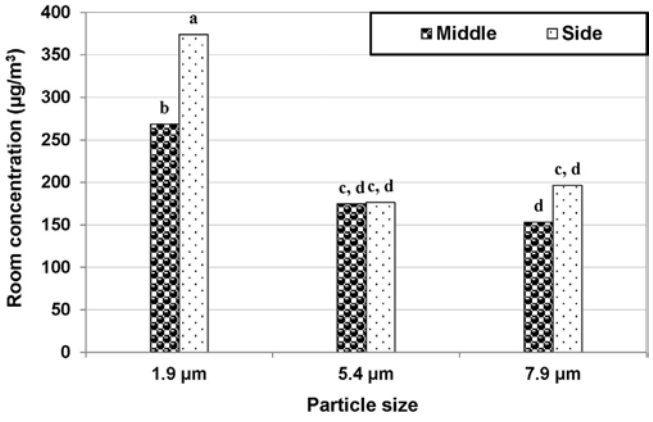


Fig. 6. Effects of particle size and injection location (across all ventilation rates) on PM concentrations within the room. No differences were detected in means marked by the same letter (a =0.05).

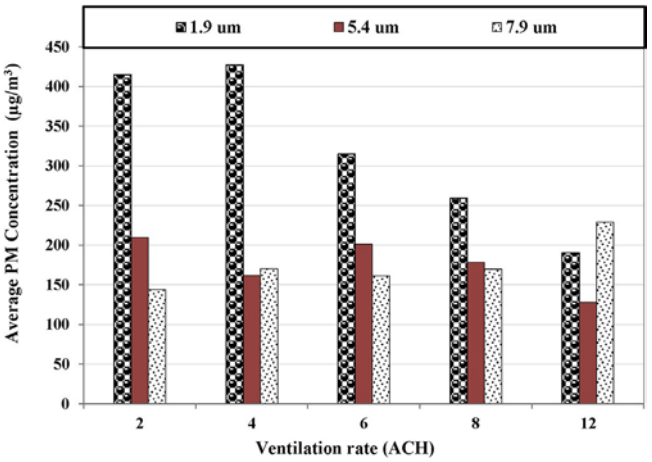


Fig. 8. Effects of ventilation rate and particle size (across both injection locations) on PM concentrations within the room.

decreased exponentially. However, as discussed below, increasing ventilation rates was not uniformly effective for reducing within-room concentrations across all particle sizes.

Fig. 6 shows average PM concentrations of room air as a function of injection location and particle size. Concentrations for the smallest particles (1.9 µm), injected in the middle or side of the PTC, were significantly higher than for the other particle sizes. Only for these smallest particles did injection location affect average concentrations in the room. However, as seen in Fig. 7, most of the differences for 1.9 µm were observed at the lowest observed ventilation rate. Concentrations were uniform between injection locations for ventilation rate of 4 ACH and greater.

Effects of ventilation rate and particle size on PM concentrations of room air samplers are shown in Fig. 8. Concentrations within the PTC for particle size of 1.9 µm were significantly higher than for larger particle sizes (5.4 and 7.9 ṁm) for each ventilation rate. For 1.9 µm particles, average concentrations at 2 and 4 ACH were significantly higher ($p < 0.05$) than for higher ventilation rates (6, 8 and 12 ACH). Assuming a constant face velocity across room-air filters, ventilation costs would be expected to increase linearly with increasing ventilation rate, but increasing ventilation rates above 6 ACH did not reduce within-room particle concentrations for any particle size. These findings are consistent with the findings of the study by Faulkner et al. [23] which used the same chamber and ventilation system used in this study, but used larger particles (18 µm).

Effects of ventilation rate and particle size on PM concentrations at the exit filter are shown in Fig. 9. Concentrations at the exit filter for particle size of 1.9 µm were significantly higher than for larger particle sizes (5.4 and 7.9 µm), which had similar exit concentrations for each ventilation rate. For 1.9 µm particles, average concentrations decreased linearly with increasing ventilation, while similar trends were not seen for the larger particles, for which the marginal benefit of increased ventilation was much lower. No significant differences in exit concentrations were observed for ventilation rates from 4 to 12 ACH for 5.4 or 7.9 µm particles.

The primary objective of this study was to determine the influence of air exchange on particulate concentrations in the occupied zone and it was not designed to determine the fate of the particles, other than measuring the particle mass that exited the chamber through the outlet. Deposition on surfaces was likely a primary fate of the particles but deposition was not determined.

3.2. *Air exchange and turbulence intensity results*

Results of air exchange and turbulence intensity measurements are shown in Table 3. The table shows the target and measured air exchange rates in ACH. The measured ACH values were reasonably

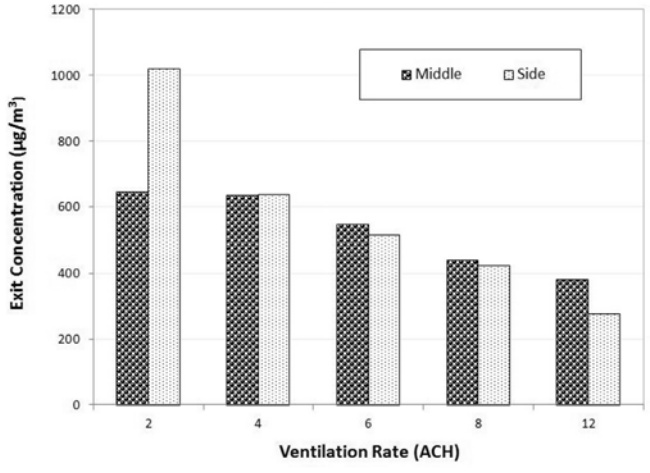


Fig. 7. Effects of ventilation rate on PM concentrations at the exit filter for 1.9 ṁm particles injected at two different locations.

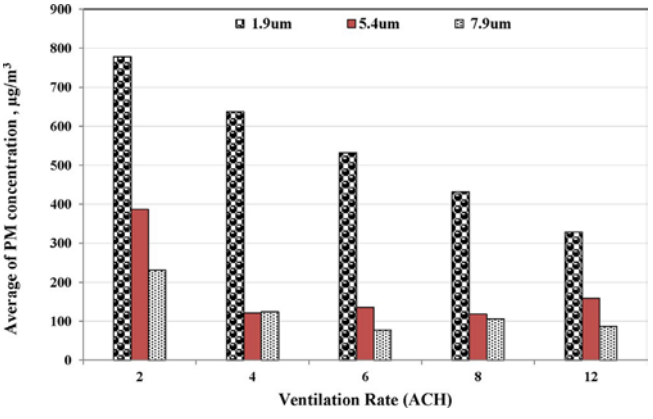


Fig. 9. Effects of ventilation rate and particle size (across both injection locations) on PM concentrations at the exit filter.

Table 3
Air exchange rates and turbulence intensity at inlet.

Target air exchange rate (ACH)	Measured inlet velocity (m s^{-1})	Measured turbulence intensity at inlet (%)	Measured air exchange rate (ACH)
2	5.3	5.8	1.47
4	4.8	9.2	4.12
6	4.7	8.7	5.25
8	5.2	1.7	9.87
12	4.5	12.5	12.9

close to the target ACH values but not exact. The values were not precise primarily because of initial inaccurate programming of the control software. Average measured inlet velocities varied between 4.5 and 5.3 m s^{-1} and our target was 5 m s^{-1}. While the linear velocity was relatively consistent for different ventilation rates, turbulence intensities increased with increasing ventilation rates. Turbulence intensities greater than 10% are generally considered to be high whereas values between 1% and 10% would be moderate [51], so all but the 12 ACH tests had turbulence intensities in the moderate range.

3.3. Fuzzy logic analysis

Statistical analysis is an excellent method of distinguishing differences between two or more groups where it is easy to distinguish between groups. Each group is typically distributed in a normal bell curve or other predefined distribution pattern. However, there are many situations where one is trying to distinguish patterns or trends in results that are not as well defined; this is especially true when it is more difficult to distinguish between one group and another group, i.e., the boundaries between the groups are fuzzy and not precisely defined. Individual data points may fit the definition of more than one group but may fit one group a little better than it fits another group. It is relatively easier for people to distinguish patterns in data but it has been more difficult to calculate these patterns using mathematical methods. Many researchers have developed fuzzy logic analysis methods that follow the basic principles presented by Zadeh [52] in order to provide a way to classify patterns by mapping numeric data into groups that are divided by linguistic terms, e.g. low, medium and high. Thus, one can use fuzzy reasoning to infer the degree of membership of each numeric data point into linguistic group such as low, medium and high.

The goal here was to assess trends in the data from this study by a simple fuzzy logic approach that was described by Faulkner et al. [23]. We divided each set of data into a small number of linguistic groups (e.g., low, medium and high groups if the data were divided into three groups). Exact numbers were calculated to give the numeric values of the boundaries of each linguistic group. The occurrences of linguistic groups for various combinations of data were tabulated to determine if there were any patterns that were less fuzzy and had more certainty. For this study, the input variables of ACH level and inlet particulate size were each divided into three groups - low, medium, and high. The output variables were divided into five groups - R1, R2, R3, R4 and R5. The output variables analyzed were: exit filter particulate concentration and the average of the particulate concentration of all the samplers in the occupied room zone.

If there were significant trends demonstrated for the output groups that corresponded to the input groups, then there would be more certainty (less fuzziness) that the trends were real. For example, if the output groups showed a significant trend of going from low to high (from R1 to R5) while the input groups went from low to high, then there would be more certainty that the output factor was significantly influenced by the change in the input factor. However, if there was a more random distribution of the output groups within the input groups, then there was more uncertainty that there was an influence. The following general conclusions state the more clear observations that were made from the fuzzy logic analysis.

For the middle injection location:

- There was a slight increase in room particle concentration with a decrease in particle size for the lower ACH values, but no trends were observed for the higher ACH values.
- There was no observable trend in exit filter concentration with changes in ACH or changes in particle size.

For the side injection location:

- There was an increase in room particle concentration with a decrease in particle size for the lowest ACH value, but not the mid-to-high ACH values.
- There was an increase in exit filter concentration with a decrease in particle size for the low-to-mid ACH values, but not the highest ACH value.

3.4. Relevance to ventilation of hospital rooms

Other researchers have studied the effects of ventilation systems in hospital rooms and were discussed previously in the Introduction of this paper. For convenience, the relevant factors and findings from those studies have been summarized in Table 4, along with the findings from this study. As can be seen from Table 4, these studies provide insights on hospital room ventilation where cross-contamination from source to recipient is a major concern. However, the results are often conflicting and do not lead to clear guidelines on how to ventilate these rooms. In addition, many of the studies are based on assumptions or tests with gases or particles less than 1 ṁm in diameter, which can be considered to follow Brownian motion of the airflow [53]. Although many bacteria and viruses are in that size range, many are transported by particulates in the room such as squames that are much larger (4-10 ṁm) [54]. Contamination from bacteria laden particulates is a major concern in healthcare facilities [34]. Particles larger than 1 ṁm will more readily settle out of air by gravity forces but can be easily re-suspended by occupant movement or activities such as shaking the bedding. Consequently, just modeling gaseous or very fine particles does not give a complete picture of how cross-contamination may occur within hospital rooms.

Results of our study would suggest that particles in the 2-8 μm diameter range are evenly distributed in a room with a cross-flow, dilution ventilation system (sidewall to sidewall). This system was better at removing the 2 μm particles from the room than it was for the 5-8 μm particles. The ventilation system in our test chamber was simple which is good for providing empirical data for verifying models. However, one should use caution when trying to directly project these findings to more complex rooms and ventilation systems. Although the test room size in this study is smaller than a typical hospital room (¾ scale of a full-size room), the data can be

Table 4
Comparison of studies on room particulate concentrations with various hospital room ventilation strategies.

Researchers	Ventilation system studied	ACH	Test type	Particle size	Findings on room particulate concentrations
Beggs et al. [34]	1. Supply low in one wall and exhaust high in opposite wall	6	CFD	<1 m	High room concentrations
	2. Supply high in one wall and exhaust low in opposite wall	6	CFD	<1 m	High room concentrations
	3. Supply in one end of ceiling, exhaust in other end of ceiling	6	CFD	<1 m	Lowest room concentrations (1/5e1/4 of strategies 1 and 2)
Zhang and Chen [36]	1. Supply in ceiling and exhaust in wall	43	CFD	0.31 m	High room concentrations
	2. Supply in wall and exhaust in opposite wall	22	CFD	0.31, 1 and 4.5 m	High room concentrations
	3. Underfloor displacement	7	CFD	0.7 m	Lowest room concentrations
Qian et al. [17]	1. Mixing ventilation	4	Empirical*	Tracer gas	Contaminated exhalation jet from mannequin quickly diluted
	2. Downward flow ventilation	4	Empirical*	Tracer gas	Contaminated exhalation jet from mannequin quickly diluted
	3. Displacement ventilation	4	Empirical*	Tracer gas	Contaminated exhalation jets from mannequin may become locked in a thermally stratified layer in occupied zone
*Breathing mannequins in beds simulated source and recipient patients in one room.					
Cheong and Phua [38]	1. Supply diffuser center of ceiling and exhaust diffuser in ceiling near a wall	30	CFD	<1 m	Highest concentration in occupied zone
		30	Empirical	Tracer gas	Empirical validation study for Strategy 1
	2. Supply diffuser center of ceiling and exhaust diffuser in wall near floor	30	CFD	<1 m	Occupied zone concentration half that of Strategy 1
	3. Supply grilles in ceiling near a wall and exhaust grilles in nearby wall near floor	30	CFD	<1 m	Occupied zone concentration half that of Strategy 1
Current Study	Round supply in wall and round exhaust opposite wall	2e12	Empirical	1.9, 5.4 and 7.9 m	Occupied zone concentrations were even across all particle sizes and air exchange rates. Mass concentration/unit air of 1.9 m was higher than for the larger particles.

used to validate future CFD models to assess system performance elements such as airflow pattern, distributions of contaminant concentration and air velocity. Small-scale experimental models are useful and less expensive surrogates than a full size model if they are scaled appropriately [55]. The chamber did not contain heat sources or obstructions, and the inlet/outlet system was not typical for ventilated hospital rooms. The relatively high inlet velocity should create a mixed ventilation area in the occupied zone, and this is confirmed by the uniform concentrations of particulates throughout the occupied zone. More empirical data of the movement of these larger particles in ventilated hospital rooms is needed in order to validate models which can be used to develop guidelines for reducing cross-contamination. Variables that need to be observed include rooms having obstructions, production of thermal plumes and movement of occupants.

4. Conclusions

The following conclusions can be drawn from the conditions tested in this study:

- Regardless of ventilation rate, particle size, and injection location, aerosol concentrations during a given test were relatively uniform throughout the occupied zone of the PTC. Therefore, for the conditions in this study, the particles were distributed evenly throughout the occupied zone regardless of the air exchange rate or particle injection location.
- For the smallest (1.9 μm) particles studied, increasing ventilation rate reduced concentrations in the occupied zone, indicating that increasing ventilation rate may provide increased protection for room occupants for these smallest particles. For the larger (5.4 and 7.9 μm) particles, increasing ventilation rate above 4 ACH did not reduce within-room exposure levels.
- The mass concentrations per unit of air of the 1.9 μm particles in the occupied zone were higher than mass concentrations of the larger particles for all observed ventilation rates below 12 ACH.
- Concentrations at the exit filter of the PTC for 1.9 μm particles were significantly higher than for larger particle sizes (5.4 and 7.9 μm), which had similar exit concentrations for each ventilation rate. For 1.9 μm particles, average concentrations decreased linearly with increasing ventilation, while similar trends were not seen for the larger particles, for which the marginal benefit of increased ventilation was much lower.
- More empirical data of the movement of larger particles in ventilated hospital rooms is needed in order to validate models which can be used to develop guidelines for reducing cross-contamination. More research is needed to provide data on rooms with obstructions, thermal plumes and movement of occupants.

References

[1] Heederik D, Sigsgaard T, Thorne PS, Kline JN, Avery R, Bonlokke JH, et al. Health effects of airborne exposures from concentrated animal feeding operations. Environ Health Perspect 2007;115(2):298-302.
[2] Just N, Duchaine C, Singh B. An aerobiological perspective of dust in cage-housed and floor-housed poultry operations. J Occup Med Toxicol 2009;4:13.
[3] Memarzadeh F. Effect of reducing ventilation rate on indoor air quality and energy cost in laboratories. J Chem Health Saf 2009;16(5):20e6.
[4] Guidelines for design and construction of hospital and health facilities. Washington DC: The American Institute of Architects Press; 2001.
[5] Guide for the care and use of laboratory animals. 8th ed. Washington DC: National Academy Press; 2011.
[6] Zhang Y. Indoor air quality engineering. New York, NY: CRC Press; 2004.
[7] ASHRAE. ASHRAE position document on airborne infectious diseases. Atlanta, GA: ASHRAE; 2014.
[8] Siegel JD, Rhinehart E, Jackson M, Chiarello L. Guideline for isolation precautions: preventing transmission of infectious agents in healthcare settings. Atlanta: Centers for Disease Control and Prevention, The Healthcare Infection Control Practices Advisory Committee; 2007.
[9] Memarzadeh F, Xu W. Role of air changes per hour (ACH) in possible transmission of airborne infections. Build Simul 2012;5:15-28.

[10] Duguid JP. The size and the duration of air-carriage of respiratory droplets and expelled from the human respiratory tract during expiratory activities. J Aerosol Sci 1945;40:256-69.
[11] Morawska L, Johnson G, Ristovski Z, Hargreaves M, Mengersen K, Chao C, et al. Droplets expelled during human expiratory activities and their origin. In: Proceedings 11th international conference on indoor air quality and climate; 2008. p. 1023. Copenhagen, Denmark.
[12] Qian H, Li Y, Nielsen PV, Hyldgaard CE, Wong TW, Chwang ATY. Dispersion of exhaled droplet nuclei in a two-bed hospital ward with three different ventilation systems. Indoor Air 2006;16:111-28.
[13] Lin Z, Wang J, Yao T, Chow TT, Fong KF. Numerical comparison of dispersion of human exhaled droplets under different ventilation methods. World Rev Sci Technol Sustain Dev 2013;10(1,2,3):142-61.
[14] Li Y, Leung GM, Tang JW, Yang X, Chao CYH, Lin JZ, et al. Role of ventilation in airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review. Indoor Air 2007;17:2-18.
[15] Lai ACK, Cheng YC. Study of expiratory droplet dispersion and transport using a new Eulerian modeling approach. Atmos Environ 2007;41(35): 7473-84.
[16] Gao NP, Niu JL. Modeling particle dispersion and deposition in indoor environments. Atmos Environ 2007;41:3862-76.
[17] Qian H, Li Y, Nielsen PV, Hyldgaard CE. Dispersion of exhalation pollutants in a two-bed hospital ward with a downward ventilation system. Build Environ 2008;43(3):344-54.
[18] Chao CYH, Wan MP. A study of the dispersion of expiratory aerosols in unidirectional downward and ceiling-return type airflows using multiphase approach. Indoor Air 2006;16(4):296-312.
[19] Wan MP, Chao CYH. Transport characteristics of expiratory droplets and droplet nucei in indoor environments with different ventilation air flow patterns. J Biomech. Eng. Trans ASME 2007;129(3):341-53.
[20] Wan MP, Chao CYH, Ng YD, Sze To GN, Yu WC. Dispersion of expiratory droplets in a general hospital ward with ceiling mixing type mechanical ventilation system. Aerosol Sci Technol 2007;41:244-58.
[21] McNeil J, Zhai Z. Critical review on hospital surgical room and mechanical systems designs. World Rev Sci Technol Sustain Dev 2013;10(1,2,3):5-16.
[22] Zhao B, Zhang Z, Li XT. Numerical study of the transport of droplets or particles generated by respiratory system indoors. Build Environ 2005;40: 1032-9.
[23] Faulkner WB, Memarzadeh F, Riskowski G, Hamilton K, Chang CZ, Chang JR. Particulate concentrations within a reduced-scale room operated at various air exchange rates. Build Environ 2013;65:71-80.
[24] Abduladheem A, Sahari KSM, Hasini H, Ahmed W, Mahdi RA. Ventilation air distribution in hospital operating room-review. Int J Sci Res (IJSR) 2013;2(11).
[25] Zhai Z, Osborne AL. Simulation-based feasibility study of improved air conditioning systems for hospital operating room. Front Archit Res 2013;2: 468-75.
[26] Memarzadeh F, Jiang J. A methodology for minimizing risk from airborne organisms in hospital isolation rooms. ASHRAE Trans 2000;106(2): 731-47.
[27] Zhao B, Zhang Y, Xianting Li X, Yang X, Huang D. Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method. Build Environ 2004;39:1-8.
[28] Coronado VG, Beck-Sague CM, Hutton MD, et al. Transmission of multidrug-resistant *Mycobacterium tuberculosis* among persons with human immunodeficiency virus infection in an urban hospital: epidemiologic and restriction fragment length polymorphism analysis. J Infect Dis 1993;168(4): 1052-5.
[29] Bloch AB, Orenstein WA, Ewing WM, et al. Measles outbreak in a pediatric practice: airborne transmission in an office setting. Pediatrics 1985;75(4): 676-83.
[30] LeClair JM, Zaia JA, Levin MJ, Congdon RG, Goldmann DA. Airborne transmission of chickenpox in a hospital. N Engl J Med 1980;302(8):4503.
[31] Riley RL, Mills CC, Nyka W, et al. Aerial dissemination of pulmonary tuberculosis. A two-year study of contagion in a tuberculosis ward. Am J Hyg 1959;70:185-96.
[32] CDC. Guidelines for environmental infection control in health-care facilities. Recommendations of CDC and the Healthcare Infection Control Practices Advisory Committee (HICPAC). MMWR 2003;52(RR10):1-42.
[33] CDC. Guidelines for preventing the transmission of *Mycobacterium tuberculosis* in health-care settings. MMWR Recomm Rep 2005;54(17):1-141.
[34] Beggs CB, Kerr KG, Noakes CJ, Hathway EA, Sleigh PA. The ventilation of multiple-bed hospital wards: review and analysis. AJIC 2008;36(4):250-9.
[35] ASHRAE. ASHRAE Handbook-HVAC applications. 1999. Atlanta, GA.
[36] Zhang Z, Chen Q. Experimental measurements and numerical simulations of particle transport and distribution in ventilated rooms. Atmos Environ 2006;40:3396-408.
[37] Murakami S, Kato S, Nagano S, Tanaka S. Diffusion characteristics of airborne particles with gravitational settling in a convection-dominant indoor flow field. ASHRAE Trans 1992;98(1):82-97.
[38] Cheong KWD, Phua SY. Development of ventilation design strategy for effective removal of pollutant in the isolation room of a hospital. Build Environ 2006;41:1161-70.
[39] Chen C, Zhao B. Some questions on dispersion of human exhaled droplets in ventilation room: answers from numerical investigation. Indoor Air 2010;20: 95-111.
[40] Hussein T, Hameri K, Heikkinen MSA, Kulmala M. Indoor and outdoor particle size characterization at a family house in Espoo-Finland. Atmos Environ 2005;39:3697-709.
[41] Hussein T, AlešHruska A, Pavla Dohanyosova P, Dzumbova L, Hemerka J, Kulmala M, et al. Deposition rates on smooth surfaces and coagulation of aerosol particles inside a test chamber. Atmos Environ 2009;43:905-14.
[42] Kanaani H, Hargreaves M, Ristovski Z, Morawska L. Deposition rates of fungal spores in indoor environments, factors effecting them and comparison with non-biological aerosols. Atmos Environ 2008;42:7141-54.
[43] Pavelchak N, Palmer W, DePersis RP, London MA. A simple and inexpensive method for determining the effective ventilation rate in a negatively pressurized room using airborne particles as a tracer. Appl Occup Environ Hyg 2002;17(10):704-10.
[44] Morawska L, Johnson GR, Ristovski ZD, Hargreaves M, Mengersen K, Corbett S, et al. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. Aerosol Sci 2009;40:256-69.
[45] Zhao B, Wu J. Particle deposition in indoor environments: analysis of influencing factors. J Hazard Mater 2007;147:439-48.
[46] ANSI/AMCA Standard 210-99. Laboratory methods of testing fans for certified aerodynamic performance rating. Air Movement and Control Association International, Inc.; 2000. 30 West University Drive, Arlington Heights, IL.
[47] Thermo Scientific. Particle technology product catalog and technical reference guide. Thermo Scientific, Thermo Fisher Scientific, Fremont, CA.
[48] May KR. The collison nebulizer: description, performance and application. Aerosol Sci 1973;4:235-43.
[49] Hinds WC. Aerosol technology - properties, behavior, and measurement of airborne particles. 2nd ed. New York, NY: John Wiley & Sons, Inc.; 1999.
[50] Wanjura JD, Parnell CB, Shaw BW, Lacey RE. Design and evaluation of a low-volume total suspended particulate sampler. Trans ASABE 2005;48(4):1547-52.
[51] Inc Fluent. ANSYS fluent 6.3 user's guide - 7.2.2 determining turbulence parameters. 2006.
[52] Zadeh IA. Fuzzy sets. Inf Control 1965;8:338e53.
[53] Crowe C, Sommerfeld M, Tsuji Y. Multiphase flows with droplets and particles. Boca Raton, Florida: CRC Press; 1998.
[54] Memarzadeh F, Manning S. Reducing the risks of surgery. ASHRAE J 2003, February:28-33.
[55] Chen Q, Lee K, Mazumdar S, Poussou S, Wang L, Wang M, et al. Ventilation performance prediction for buildings: model assessment. Build Environ 2010;45(2):295-303.