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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 e 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 10e15 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 mm [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 mm [7e9]. 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 e 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 e these dimensions were 0.79 cm and 26.7 cm; for 6 ACH e 0.148 cm and 27.9 cm; for 8 ACH 1.27 cm and 27.9 cm; and for 12 ACH e 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).

Fig. 2. Air inlet system e particulates were injected into this horizontal inlet pipe on the right hand side and the stainless steel inlet is shown fastened to the PTC on the left hand side.

flowed through a horizontal 15.2 cm diameter SCH 40 PVC pipe to a HEPA filter and a precision airflow nozzle. The pipe then moved the air through a 10.2 cm diameter SCH 40 vertical pipe up to a horizontal straight section of pipe that moved the air to the PTC inlet (Fig. 2). Particulates were injected into the inlet airflow just prior to the straight section of pipe against the flow of air to uniformly distribute particulates in the air stream. The particulate laden air then passed through the inlet into the chamber.

The precision nozzles used to measure airflow (Kurt J. Lesker, Inc., PA) had a 2.5 cm diameter for the 2 and 4 ACH runs and a 5 cm diameter for the 6, 8, and 12 ACH runs. The pressure drop across the precision nozzle was measured with a Dwyer Instruments gage (Part number 677-7). There were four flush mounted pressure taps in the PVC pipe located 15.2 cm before the pressure nozzle and four flush mounted pressure taps on the outlet end of the precision nozzles. The HEPA filter was a Hepa-Pleat II (Model STD14-14-03-EHDC30) and it was 35.6 by 35.6 cm. After the HEPA filter was an Omega (Model HX94AC) temperature/relative humidity sensor. There was a 116.8 cm straight section of pipe between the HEPA filter and the precision airflow nozzle, then a 106.7 cm straight section of pipe after the nozzle before an elbow turned the air vertically.

The incoming air was seeded with particulates and mixed to a uniform distribution to achieve an average particle mass density (particulate mass per volume of air) of around 2000 mg/m^3 in the inlet air. The particulate mass density entering the PTC through the inlet was calculated based on the particulate density and airflow through the inlet. The particulates were corn starch (mass median diameter (MMD) ¼ 17.95 mm aerodynamic equivalent diameter (AED), geometric standard deviation (GSD) ¼ 1.41, density ¼ 1.5 g/cm^3 [11]). One of the more critical ventilation situations is removing pathogen laden particles that result from the sneezing and coughing of patients in health facilities. Pathogens are often contained in droplets from sneezing that are up to 20 mm range when first ejected [9]. These larger particles are more challenging for the ventilation system to remove them from the vicinity of susceptible recipients in the occupied zone of a room. We selected particle sizes in the higher range to observe ventilation effectiveness at the more challenging situation.

Particulates were metered into the system with a Wright Dust Feeder II system (BGI Inc., MA). The particle mass feeding rate was calculated based on the manufacturer's calibration of the dust feeder rpm versus the dust mass feeding rate. It was assumed that when the particles were packed into the dust feeder cartridges, the overall density was equal to the particle density (1.5 g/cm^3). The dust feeder required a small amount of airflow (0.034 m^3/min) to pick up the particulates and carry them into the inlet air stream. This dust feeder air was supplied by a compressed air system and the air was filtered and passed through a desiccator just prior to entering the dust feeder.

Because corn starch is hygroscopic, it had to be kept in dry conditions at all times to prevent it from forming clumps that plugged the dust feeder. Particulates were loaded into a small cartridge then packed in with a press. The Wright Dust Feeder II system would scrape a precise amount of particulates from the packed mass in the cartridge over time and inject the loose particulates into the inlet pipe.

The experimental run time was set at 1.5 h to allow sufficient time to collect enough particulate mass on each filter located in the PTC for analysis. The amount of particulates collected in this period was sufficient to obtain good data for the particle mass analysis. However, about 19% of the data from the particle size distribution tests were outliers, partially because there were insufficient amounts of particles collected on the filters for an accurate measurement.

2.3. Air outlet system

Air was drawn out of the PTC through a stainless steel pipe 26.7 cm long, then through an outlet filter (Fig. 3). The outlet pipe inside diameter varied with airflow and matched the inlet diameters. A vacuum blower was placed beyond the outlet filter to draw air from the PTC. The inlet and outlet fans were adjusted to

Fig. 3. Outlet system e showing outlet tube to filter to vacuum pump.

maintain the desired air changes per hour through the PTC and to maintain a negative pressure in the chamber of at around 25.5 Pa. A glass fiber filter (HI-Q brand, part number FP2063-810) was used for the outlet and was weighed prior to and after each experimental run. Filter size for the outlet varied depending 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. Different sizes of filter holders were used for the different size filters.

2.4. Particulate sampler system

Twelve total suspended particulates (TSP) samplers were installed within the PTC to measure particulate mass density levels at 12 locations (Table 1 and Fig. 4). Six TSP samplers were evenly spaced at 1/3H and the other six samplers were evenly spaced at 2/3H and coded according to their location. The TSP samplers were a low-volume design [12].

There was one air pump and filter system for each TSP sampler and they were located just outside of the PTC (white boxes in Fig. 1). Each sampler drew 0.0167 m^3/min of air through a filter (47 mm diameter PTFE). Airflow through each sampler was continuously monitored with a sharp edged orifice and pressure transducer connected to a HOBO data logger, and these measured values were used in the analysis. In order to maintain air balances within the PTC, this air (total of 0.2 m^3/min) was re-injected into the PTC through a low-velocity opening located in the lower section of one side wall near the outlet endwall of the PTC.

2.5. Control system

The airflow system was controlled by a LabVIEW program developed for this project. This program controlled the inlet and outlet fans to obtain the airflow through the PTC while maintaining a negative static pressure within the PTC of around 25.5 Pa. LabVIEW recorded data on static pressure, barometric pressure, and PTC temperature and relative humidity. The static pressure was measured with a Dwyer Instruments gage (Part Number 677-4) and a Dwyer Instruments manometer, and had 2 taps – one into the front wall and one into the back wall of the PTC. Barometric pressure was measured with a Cole–Parmer gage (Part Number 98072-38).

2.6. Turbulence intensity tests

The turbulence intensities were measured at the PTC inlet. Measurements were made with a TSI Model 8455 Thermal Anemometer (TSI Inc., Shoreview, MN) controlled by an NI Model CFP-AI-110 Controller. The thermal anemometer was a unidirectional air velocity transducer with a range of 0.13–50 m/s and an accuracy of ±2% of reading. The controller collected data at one time per second. Measurements were taken at 3 points across the width of inlet (centered vertically across the height) - the center and ¼ of the inlet diameter off center in either direction along the y-axis. The velocity was logged for 120 s and a total of at least 120 readings were taken for each value. Turbulence Intensity is defined as:

$$T.I. = \sigma'/U$$

Where:

T.I. = turbulence intensity – one dimensional
σ' = Standard Deviation of velocity readings
U = average of velocity readings

Fig. 4. Room particulate sampler system – 12 samplers at two heights, three depths, and two cross-section locations.

Table 1
Room particulate sampler locations, cm. The zero point of all three coordinates is the lower, left hand corner of the inlet end wall of the PTC. The x-axis runs along the length, the y-axis along the width, and the z-axis along the height of the PTC.

Sampler ID	X – Coordinate	Y – Coordinate	Z – Coordinate
A	95	67	138
B	95	67	72
C	95	135	138
D	95	135	72
E	191	67	138
F	191	67	72
G	191	135	138
H	191	135	72
I	288	67	138
J	288	67	72
K	288	136	138
L	288	136	72
Inlet	0	102	153
Outlet	386	102	153

2.7. Experimental run with particulates

The experimental procedure for this study was designed to have:

- 5 levels of air changes per hour, ACH – 2, 4, 6, 8, 12 ACH (inlet diameter was varied to maintain a constant air velocity of around 5.1 m/s across all ACH treatments)
- 2 levels of turbulence intensity at the air inlet
- 3 replications

There were 5 × 2 × 3 = 30 experimental runs.

As discussed earlier, the different turbulence intensities were (N) no obstruction in the inlet and (T) a small rod across the inlet.

The airflow system through the PTC was allowed to operate for at least 8 min prior to sampling of the particulate levels in the PTC in order to allow the airflow within the PTC to stabilize. The samplers were turned on after the dust feeder was started to avoid sampling clean air that would skew the data. The system was operated with the particulates being injected for around 1.5 h and then shut down.

The filters were conditioned at controlled temperature and relative humidity for a minimum of 24 h before weighing. Each filter was weighed three times. If the standard deviation of the weights was less than 50 μg, the average of the three weights was used. If the standard deviation was greater than 50 μg, the filters were reweighed. The filters used were 47 mm PTFE membrane filters.

A Malvern Mastersizer 2000 (Malvern Instruments Ltd., Worcestershire, UK) was used to determine a particle size distribution of the captured particles. The standard operating procedures for the particle size distribution analysis were provided by Malvern Mastersizer manufacturer. The Malvern Mastersizer gave data that was used to calculate the Mass Median Diameter (MMD) and the Geometric Standard Deviation (GSD). For a given particle population, the MMD is the diameter at which half of the mass has small diameters and half of the mass has larger diameters. GSD (or s_g) is the standard deviation of the logarithms.

3. Results and discussion

The actual ACH values were somewhat different from the desired ACH because incorrect numbers for the inlet diameters were entered into the LabVIEW control program and this program adjusted the airflow into the chamber based on inputted inlet diameter values that were somewhat different from the actual inlet diameters. This fact was not discovered until the runs were completed. The target and calculated actual chamber ACH values and inlet air velocity values are given in Table 2.

3.1. Particulate concentration results

Figs. 5 and 6 show the averages for the inlet and outlet concentrations across ACH conditions for both the low and high turbulence conditions, respectively. Fig. 7 shows the averages of all 12 room samplers across the various ACH conditions. In addition, Fig. 8 shows the averages of the front (A-D), center (E-H), and back (I-L) samplers across the various ACH and turbulence conditions.

The outlet particulate concentrations were considerably lower than the calculated inlet particulate concentrations (Figs. 5 and 6). This was likely due to particles settling out or impacting chamber surfaces. The outlet concentrations generally increased as ACH increased, primarily because the number of particles injected into the room increased as the ACH increased. The T turbulence tests generally had slightly higher outlet concentrations than the N turbulence tests, but these differences were not significant. The room particulate concentrations, as measured by the samplers at locations A through L, were much lower than the outlet particulate concentrations because the particle concentration near the outlet would likely have been higher. In this study, the particles were injected into the chamber through the air inlet jet which would have carried the particles directly towards the outlet first. Then the particles would move down into the occupied zone towards the back of the chamber due to gravitational settling, secondary airflow patterns, and diffusion.

3.2. General trends for room particulate concentrations as measured by the room samplers

For all the conditions studied, particulate concentration measured by the room samplers increased with increasing ACH e although the concentrations leveled out at the higher ACH runs. In general, the T turbulence conditions had slightly higher particulate concentration at the room samplers and the outlet than the N turbulence conditions but these differences were not statistically

Table 2
Target versus actual chamber ACH and inlet air velocity.

Target ACH	2	4	6	8	12
Actual ACH	2.3	3.6	5.36	9.2	14.4
Target Air Velocity, m/s	5.1	5.1	5.1	5.1	5.1
Actual Air Velocity, m/s	5.9	4.6	4.5	5.8	6.1

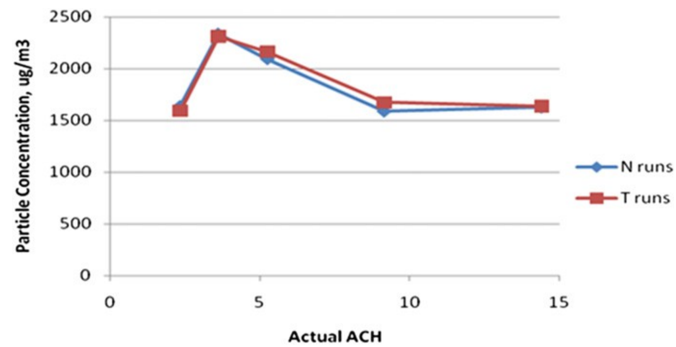

Fig. 5. Calculated air inlet particulate concentrations across the various ACH conditions. N is for tests with no turbulence rod in the inlet. T is for tests with a turbulence rod in the inlet.

different. The particulate concentrations toward the front (inlet end) of the PTC were slightly lower and the concentration increased towards the back of the PTC. The particle-laden air jet would likely have moved downward into the occupied zone towards the back of the chamber so the occupied zone at the back of the chamber would have received a higher load of particles initially. The lower concentrations at the front of the chamber may be a result of the larger particles settling out of the secondary air flow pattern in the occupied zone as the air moved from the back to the front.

The variation of the particulate concentrations tended to be high because it was difficult to inject the relatively low concentrations of particulates at the specified low air exchange rates.

3.3. Particle size distribution at room samplers

The MMD and GSD data were averaged for the replications. About 19% of the data from these particle size distribution tests were outliers, partially because there were insufficient amounts of particles collected on the filters for an accurate measurement in the Malvern Mastersizer. Most of the MMD and GSD results were scattered across sampler location, ACH, and turbulence conditions and do not demonstrate trends. One trend that is shown in Fig. 9 is that the average MMD across all samplers decreased as ACH increased, indicating that larger particles were removed from the occupied zone more effectively at higher air exchange rates.

3.4. Turbulence intensity tests

Results of the turbulence intensity measurements at the air inlet are in Table 3. Velocity readings were taken at one reading per

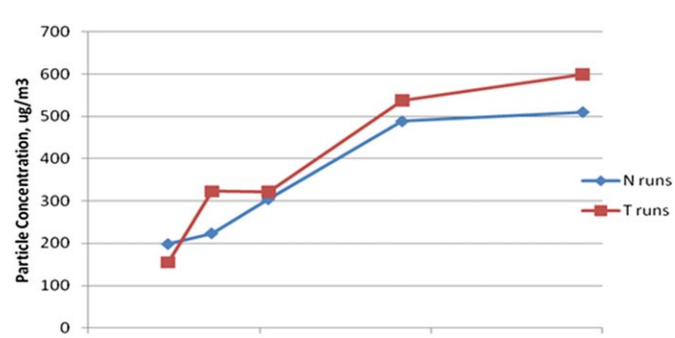

Fig. 6. Comparison of air outlet particulate concentrations across the various ACH conditions. N is for tests with no turbulence rod in the inlet. T is for tests with a turbulence rod in the inlet.

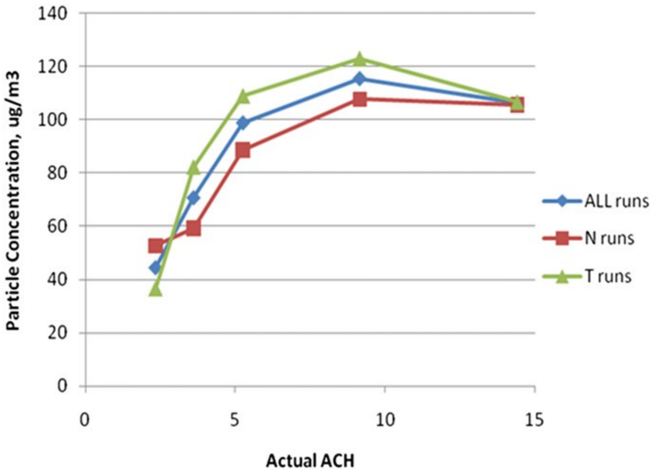

Fig. 7. Comparison of room sampler particulate concentration measurements across the various ACH conditions.

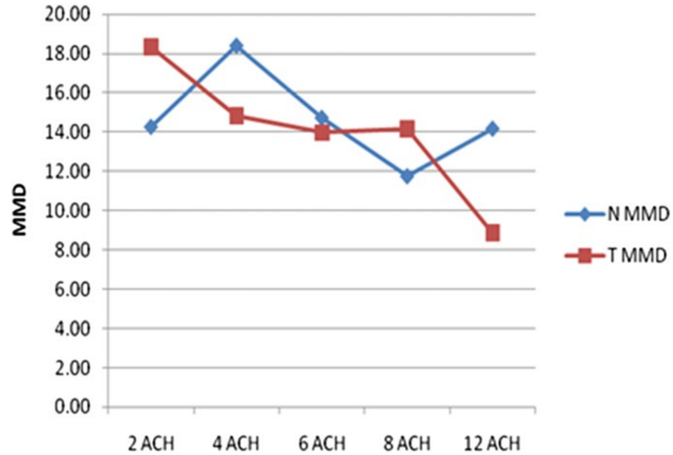

Fig. 9. MMD values across desired ACH values e averaged for all sampler locations. ACH values given are the desired ACH.

second which is lower than desired for turbulence intensity calculations. The values range from around 0.3e1.5% which is a low to moderate level of turbulence intensity. The average turbulence intensity values for the three locations for the runs labeled as (T) actually had a slightly lower turbulence intensity on average than the runs labeled as (N). However, the center location values were lower for the N runs than for the T runs. For the N runs, the center of the inlet had an average turbulence intensity of about one-half of that at either side. For the T runs, the turbulence intensities were on average more even across the inlet. The center measurement represents 25% of the total inlet area and the two outer measurements can be considered to be combined to represent 75% of the area. The turbulence bars were located at the center of the opening and oriented vertically. Apparently, the bars increased the turbulence at the center where they were located but reduced turbulence in the outer part of the inlet.

3.5. Statistical analysis

Analysis of variance (ANOVA) tests were performed on measured TSP concentrations using StatEase software (StatEase, Minneapolis, MN) to determine whether there was impact of target ACH, turbulence level, sampler lateral distance from inlet, or sampler elevation on particulate concentrations. Covariates analyzed included: actual ACH, dust feed rate, inlet air concentration, room temperature, barometric pressure, and room pressure. Outlet particulate concentrations were a response variable and were not included. Sampler particulate concentrations were not significantly impacted by sampler elevation (p ¼ 0.792) or the covariates dust feed rate, temperature, relative humidity, or barometric pressure. The final model ($p < 0.0005$) is shown in Table 4.

Concentrations measured in the room varied with Target ACH ($p < 0.0005$). Because the airflow system did not maintain the exact Target ACH, Actual ACH was entered as a covariate which explained additional variation in concentrations beyond that predicted by the Target ACH ($p < 0.0005$).

The turbulence level at the inlet did not explain variations in concentrations (p ¼ 0.170), but the interaction between Target ACH and turbulence was significant ($p < 0.0005$). This interaction was significant because concentrations varied between turbulence intensity treatments when ACH ¼ 2 but not for any other ACH treatment.

Sampler elevation did not significantly affect measured concentrations, but the lateral distance from the air inlet did (p ¼ 0.002).

Variations in inlet particle concentrations ($p < 0.005$) and room pressure relative to barometric (p ¼ 0.002) also explained variations in inlet concentrations beyond those explained by the independent variables.

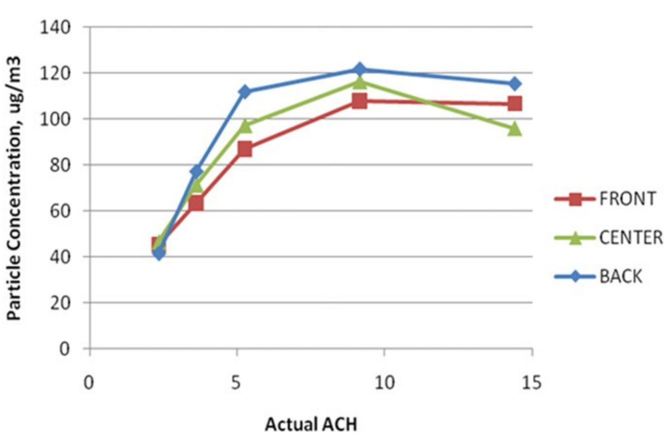

Fig. 8. Comparison of averages of front (AeD), center (EeH), and back (IeL) room samplers across all the various ACH and turbulence conditions.

Table 3
Turbulence intensity results at air inlet, %. There were no statistical differences between N and T for any of the ACH levels. The average left and right N values were statistically higher than the average center N value ($p < 0.1$). There were no statistical differences between the other left, center and right values.

	Left	Center	Right	Avg
2N	0.821	0.317	1.21	0.781
2T	0.675	0.290	0.388	0.451
4N	0.699	0.307	0.774	0.593
4T	0.522	0.670	0.545	0.579
6N	0.830	0.405	0.726	0.654
6T	0.543	1.14	0.627	0.769
8N	1.07	0.481	0.950	0.834
8T	0.863	1.09	0.945	0.965
12N	1.52	0.897	1.45	1.29
12T	1.43	0.797	1.04	1.09
Avg	0.897	0.639	0.864	0.800
N Avg	0.987	0.481	1.02	0.829
T Avg	0.806	0.796	0.709	0.770

Table 4
Statistical model for particulate concentrations.

Fixed factors	
Target ACH	p < 0.0005
Turbulence	P ¼ 0.170
Sampler lateral placement	P ¼ 0.002
Covariates	
Actual ACH	P < 0.0005
Inlet concentration	P < 0.0005
Room pressure	P ¼ 0.002
Interactions	
Target ACH * Turbulence	P < 0.0005

3.6. Fuzzy logic analysis and discussion

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. Scientists have depended on statistical methods for decades to determine if various treatments have a significant effect and to test specific hypothesis. 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 relatively difficult to calculate these patterns using mathematical methods. Many researchers have developed fuzzy logic analysis methods that follow the basic principles presented by Zadeh [13] 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 extract more efficient fuzzy rules from a small set of data by a simple fuzzy logic approach. 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 concentration were each divided into three groups e low, medium, and high. The output variables were divided into five groups e R1, R2, R3, R4 and R5. The output variables analyzed were: outlet particulate concentration; the average of the particulate concentration of all the samplers in the occupied room zone; the particulate concentration of each of the samplers in the occupied room zone; and the average of the particulate concentrations for the front four samplers (ABCD), for the middle four samplers (EFGH) and the back four samplers (IJKL).

For fuzzy logic analysis, each input and output data set was divided into a reasonable number of linguistic groups. Each data set can be visualized as shown in Fig. 10 where the data values are on the x-axis and the fuzziness is given on the y-axis, where 0 is very fuzzy and uncertain and 1 is certain and not fuzzy. For the example shown here (Actual ACH), the data values are divided into three groups as shown by the different types of dashed lines. The data for the "low" group are under the line to the left with the large dashes. The data for the "medium" group are under the lines toward the

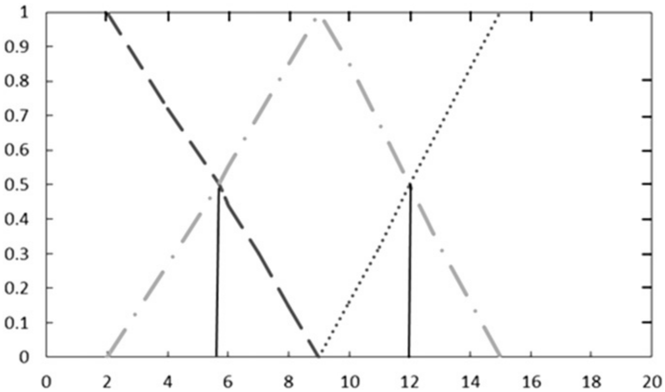

Fig. 10. Example of fuzzy logic chart. The X-axis numbers are the data values (Actual ACH in this example). The Y-axis numbers are the fuzziness values which range from 0 (very fuzzy) to 1 (not fuzzy).

center of the figure that go up and then down which are represented by the centerline symbol (dashes and dots). The data for the "high" group are under the line to the right with the dots. Note that the groups overlap when the fuzziness values are less than 0.5. The membership in one group or another is less fuzzy and more certain when the fuzziness values are between 0.5 and 1 and more fuzzy and uncertain at the lower fuzziness values. For the data that are in the more fuzzy (fuzziness less than 0.5) boundary regions between groups, we need a method to determine where each data point goes.

In this version of fuzzy logic, we divided the linguistic groups by determining the parts of the data set where the fuzziness of the different dashed lines are in the 0.5 to 1 region. For each of the forementioned factors, the data were divided into the number of linguistic groups by the following method:

First, determine the minimum (Xmin) and maximum (Xmax) value from the data set.

Second, the group interval is determined by:

D ¼ (Xmax e Xmin)/(C e 1) where 2D is the group interval and C is the number of groups in each data set.

The location along the x-axis of the minimum fuzziness value (0) and maximum fuzziness value (1) of the blue, green and red membership group lines are determined by:

$$\text{Xi ¼ ðXmin þ DÞ*i; where i ¼ 0 to ðC} - \text{1Þ}$$

In order to determine the regions where the x-axis values are in the 0.5 to 1 range of the y-axis values, we need to determine the x-axis values at which the lines intersect (the vertical orange and yellow lines in Fig. 10).

$$A_j \text{ ¼ } \left(X_j \text{ þ } X_{j\text{þ}1}\right)1_2; \text{ where j ¼ 0 to } (C-2)$$

The range of x-axis values of the linguistic groups are then determined as follows (for this example, we predetermined three groups as Low, Medium and High):

Low ¼ ðXmin; A0Þ

Medium ¼ ðA0; A1Þ

High ¼ ðA1; XmaxÞ

Once the ranges of data values were determined for each of the groups defined for the input and output data sets, we then evaluated the influence of the input factors on the various output factors. Fuzzy logic analysis was done to determine the influence of Actual

ACH, Inlet Particulate Concentration, and turbulence level on the particulate concentrations at the outlet; each sampler; the average of the front, middle and back samplers; and the average of all the samplers. Each of these analyses was done independently for N turbulence conditions and T turbulence conditions.

For the analysis, the data groups from the output factor being analyzed were matched to the data groups of the three input factors (Actual ACH, Inlet Particulate Concentration, and Turbulence Condition). The occurrence of the output data groups were given in output tables of the input groups. An example output table is shown in Table 5 for the outlet particulate concentration analysis.

If there were significant trends demonstrated in the output tables 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 group tables, then there was more uncertainty that there was an influence. The following conclusions state the more clear observations that can be made from the output tables.

3.7. Conclusions of fuzzy decision rules analysis

Influence of actual ACH values on outlet particle concentrations: For both the N and T turbulence tests, it was found that the outlet particle concentration increased with actual ACH from the low group to the higher two groups, but it was not a strong relationship because the uncertainty also increased from the lower actual ACH group to the higher groups. There were no influences demonstrated for inlet particulate concentration for this conclusion or any of the following conclusions.

Influence of actual ACH values on average room particle concentrations (Samplers A-L): For the N turbulence tests, there were no influences of actual ACH on room particle concentrations. For the T turbulence tests, there was some increase from the low actual ACH group to the higher two groups (i.e., this phenomenon is more strongly displayed than it was for the low turbulence tests), but it was not a strong relationship because the uncertainty was higher at the higher groups.

Influence of actual ACH values on room particle concentrations at the front (Samplers ABCD), middle (Samplers EFGH) and back (Samplers IJKL) of room: For both the N and T turbulence tests, it was found that there were no influences of actual ACH on concentration grouped by location (Front, Middle, Back) in the room.

Influence of turbulence condition on outlet particle concentrations: No influences were observed by this analysis. However, even at the T turbulence treatment, measured turbulence was relatively low, with a maximum value measured at the inlet of 1.5%.

Table 5
Fuzzy logic analysis output table for room outlet particulate concentration.

		Inlet particulate concentration		
		Low	Medium	High
Turbulence e N:				
Actual ACH	Low	R1; R2	R2; R3	R1
	Medium	R3		
	High	R2; R4		
Turbulence e T:				
Actual ACH	Low	R1	R2; R3	R2
	Medium	R3; R5		
	High	R3; R4		

Influence of turbulence condition on average room particle concentrations (Samplers A-L): No influences were observed by this analysis.

Influence of turbulence condition on room particle concentrations at the front (Samplers ABCD), middle (Samplers EFGH) and back (Samplers IJKL) of room: For the most part, there were not any clear influences found. However, at the T turbulence condition, the room particle concentration was slightly higher at the back location than at the N turbulence condition, but it is not a very clear characteristic.

Influence of inlet particle concentrations on all other factors: No significant influences were observed by this analysis. However, when the inlet particulate concentration was at the medium level, the occupied room particulate concentration was slightly higher than when the inlet concentration levels were low or high, but it was with higher uncertainty.

3.8. Room zone patterns to particulate concentrations

Most ventilated rooms would have incomplete mixing under steady state operating conditions. So, it is expected that contaminate concentrations will vary considerably with location in the room. This is especially true for particulates because, depending on particle size and other properties, they are less likely to follow the same paths as the air flow patterns. There is a complex interaction of the particulate inertia, drag forces from airflow, and gravity that dictates movement and deposition of particulates in confined spaces. Under steady state conditions, one could conduct a mass balance analysis to determine mass of particulates entering the chamber through the air inlet and mass of particulates exiting the chamber through the exhaust air, then assume that the remainder of the particulate mass is removed from the air by deposition onto the floor via gravity or by colliding with and adhering to walls and other surfaces. Some of the particulate mass would remain suspended in the air within the room to maintain a certain room concentration.

In the chamber tested in this study, it would be reasonable to divide the chamber volume into different zones and analyze particulate levels in the different zones and how the zones would interact with each other. For the discussion here, we will look at three zones: 1. Inlet zone, 2. Exhaust zone and 3. Occupied zone. We will not presume to have precise boundaries for each zone but will use them as concepts for discussion. The inlet zone is the region that is predominately influenced by the inlet air. The inlet air enters through a single round opening on one end of the chamber to create a jet of air that has a relatively much higher velocity than the rest of the room, and, because particles were injected into the chamber via the inlet air in this study, the inlet zone would have much higher concentrations of particulates relative to the rest of the chamber. Detailed measurements of air velocities and particulate concentrations were not taken within the inlet zone. However, based on previous studies [14], it is expected that the jet of air would traverse the length of the chamber and create a secondary circular airflow pattern within the chamber below the inlet zone. The jet would follow the coanda effect and have a slight upward flow so the inlet zone would be above the occupied zone (to be defined later).

The outlet zone would be a relatively small area around the outlet. Although the outlet diameter was sized to exhaust air at the same velocity as the air entered through the inlet, the exhaust would have little impact on room airflow patterns beyond a few outlet diameters away from the outlet opening. The occupied zone is the lower part of the room that would not be directly impacted by the inlet or the exhaust. There would be secondary impacts from the inlet zone due to drag forces. The occupied zone is the area of interest in occupied rooms because that is where humans or animals would be located and therefore the conditions in that zone are what affect health. Ideally, we could design the ventilation system (inlets, exhausts, air exchange levels, etc.) to maintain healthy conditions within the occupied zone.

The primary interest of this study was the impact of increasing the actual ACH on the occupied zone particulate concentrations. When it comes to facilities where health is a concern, the general feeling is that more air exchange is better because it will reduce concentrations of contaminants such as gases, particulates and disease organisms. However, increasing the levels of air exchange also greatly increases energy costs and greenhouse gas levels in the atmosphere because of extra energy needed to condition and move the additional air. There needs to be a balance where sufficient air exchange is provided to ensure a healthy environment in the occupied zones while at the same time not over compensating with too much air exchange that wastes large amounts of energy and money.

In this study, particulate concentrations in the inlet air were held fairly constant (Fig. 5) such that as the actual ACH increased, the amount of particulates injected into the chamber also increased. That would help explain why the particulate levels at the outlet also increased essentially linearly with an increase in actual ACH (Fig. 6). However, the particulate concentrations in the occupied zone (Samplers A to L) did not increase linearly with an increase in actual ACH (Fig. 7), indicating more complex interactions between air exchange rates and particle concentrations in the occupied zone than current ventilation practices imply. Concentrations in the occupied zone increased essentially linearly as actual ACH increased from around 2 to 5 but then leveled out at the higher actual ACH values. The higher range of actual ACH values studied here did not change the environment in the occupied zone. Fig. 11 shows the same data already presented in a different format where the particulate concentrations in the occupied zone and at the outlet are expressed as a percentage of the inlet particulate concentration. Fig. 11 shows that the outlet concentration as a percent of the inlet concentration increased from around 11% at 2 actual ACH to around 31% at around 8 actual ACH, then increased to only around 34% at around 14 actual ACH. The percent of occupied zone concentration relative to inlet concentration went from around 3% at 2 ACH to around 6% at 8 actual ACH and even decreased slightly as it went from 8 to 14 actual ACH. Overall, for the relatively simple ventilated chamber used in this study, the occupied zone particulate concentration as a percentage of inlet particulate concentration had very low response to significant increases in actual ACH. The fuzzy logic analysis also indicated little influence of actual ACH on the occupied zone particulate concentrations. Overall, this study indicates that there may be limits to the advantages of increasing ACH in terms of providing better environments in the occupied zones of rooms with some types of ventilation systems. These results indicate that further investigation is needed given the fact that increasing ACH greatly increases energy consumption and cost.

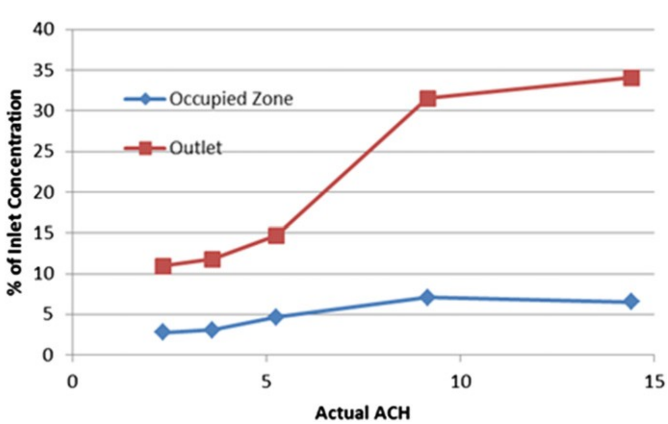

Fig. 11. Particulate concentrations at occupied zone and outlet as percentages of the particulate concentrations at the inlet.

In this study, the ventilation system of this chamber and other factors that affect occupied zone conditions were intentionally kept simple. There are several other factors that can affect conditions in the occupied zone and their effects need to be studied. These other factors would include type of ventilation system, particle size, thermal plumes from heat sources in the room, room obstructions, mechanical re-suspension of particulates from surfaces (especially from floor deposition), and particulate loads from sources and locations other than the air inlet. It is strongly recommended that further studies be conducted to isolate the impacts of these other factors to determine optimum air exchange rates that can maintain occupant health without excessive energy costs. It is particularly important to determine the impact of particulate source location and particulate load on ACH requirements.

4. Conclusions

For the conditions in this study and based on the statistical and fuzzy logic analyses, the following observations can be made.

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.

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 (up to 14 actual ACH). Increasing the air exchange rate to the higher range of ACH values studied here did not change the particulate concentrations in the occupied zone, which is the area of the room most critical to protecting the health and welfare of people and animals.

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.

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