Assessing Mitigation Strategies to Reduce Potential Exposures to Indoor Particle Release Events

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ABSTRACT

Airborne transmission is a major concern for many infectious pathogens, including the novel coronavirus. Ventilation is the principal engineering method used to control airborne health hazards in buildings. Understanding potential air pollution hazards are a particular concern for highly populated indoor environments, such as workplaces and classrooms. This study discusses the results of ventilation testing in a university classroom which contains two fan coil units as the primary HVAC system. A particle nebulizer was used to release aerosol particles into the air, and multiple particulate measuring devices were placed strategically around the room to measure the particle concentration over time. An exponential particle decay rate is determined from the data and converted to a particle concentration half-life, which ranged from over 60 minutes down to under 10 minutes. We then assess how quickly the particles were removed by ventilation systems with varying conditions, including the addition of both high- and low-cost portable mitigation devices into the classroom. Our results indicate that a low-cost unit, made of a simple box fan with a MERV13 filter taped to it, may perform as well at removing particles from a room as a high-cost HEPA filter unit, owing to a tradeoff between filtration efficiency and the number of air changes per hour. As is observed in numerous other studies, the particle concentration half-life in each classroom setup decreases as the mechanical air changes per hour increases from about 1.3 to 9.3. These results are used to evaluate the potential personal exposure risk associated with various classroom ventilation setups. Our results indicate that, when compared to running the fan coil units on low fan speed, operating on a high fan speed reduces potential exposure by 22% and using a portable HEPA filter in the room reduces potential exposure by 66%.

**Keywords:** Indoor air pollution, Filtration, Ventilation, HVAC systems
INTRODUCTION

The novel coronavirus, Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) that causes a severe respiratory disease (COVID-19) began spreading and was declared a pandemic in 2020 (Chen et al., 2020; Jayaweera et al., 2020). As with most viruses, COVID-19 is spread through various transmission routes, through direct physical contact with an infected individual, by contact with large respiratory droplets expelled by coughing, sneezing, or talking in close vicinity, or via airborne aerosol transmission (Jayaweera et al., 2020; Sommerstein et al., 2020a).

Aerosols and respiratory droplets are differentiated primarily by size. Though there is not a definitive size range for droplets and aerosols, the World Health Organization (WHO) and U.S. Centers for Disease Control and Prevention (CDC) have suggested that the particles greater than 5 μm in diameter are considered droplets, and those less than 5 μm in diameter are considered aerosols (Siegel et al., 2007; WHO, 2014). Respiratory droplets behave differently from aerosols as larger droplets are too heavy to remain suspended in air. Larger droplets, such as those expelled by coughing or sneezing, will typically fall to the ground or encounter a surface object near the point of emission (Schijven et al., 2020). On the other hand, respiratory aerosols, which can be expelled through coughing, sneezing, or even talking and breathing, can remain suspended in the air for prolonged periods of time and thus can drift farther distances than large droplets (Jayaweera et al., 2020). Aerosol transmission occurs when infectious aerosol particles are generated, and the pathogen can remain viable in the suspended aerosol. The suspended aerosol then comes into direct contact with target tissues (eyes, nose, throat) or is inhaled by a new potential host (Sommerstein et al., 2020b). Airborne particles less than 10 microns in diameter (PM₁₀) are considered respirable, meaning they can be inhaled and reach deeper levels of the lungs than larger particles. Aerosol transmission of a respiratory disease is of significant importance in the spread of COVID-19.
concern because aerosols can remain airborne for longer periods of time and can drift significant
distances, which is especially important when considering long term exposure in enclosed spaces
or buildings.

Heating, ventilation, and air conditioning (HVAC) systems are essential components in modern
buildings. HVAC systems are primarily utilized to heat and cool buildings to provide a more
comfortable temperature environment. However, HVAC systems also play a large role in the
indoor air quality of the building. Natural ventilation, such as opening doors and windows, was
once considered an easy and cost-effective method to improve indoor air quality; however, for
areas with high particulate matter (PM) concentrations in the outdoor environment, using natural
ventilation is ineffective and has the potential to worsen indoor air quality (Kim et al., 2018).

Ventilation system design can be used as a tool to decrease indoor particle concentration and
reduce the risk of infectious disease transmission (Kabrein et al., 2017). With the increasing
amount of time people spend indoors, proper ventilation systems are important, whether in an
office building, classroom, or home. HVAC systems can be largely divided into two categories:
centralized and decentralized systems.

Aerosol transport in indoor environments depends largely on the ventilation system design and
operation. Primary mechanisms of aerosol transmission in ventilation systems include the
cycling of deposition and resuspension of particles, both in the occupied spaces and furniture and
in the air ducts and filters of the HVAC system itself. Before reaching the indoor space, aerosol
particles in ducts will likely undergo several rounds of suspension and deposition within the
ducts (Liu et al., 2018). The deposition of aerosols in ventilation ducts is affected by various
factors, including particle size, duct bend and bifurcation, duct rib shape and rib arrangement,
and the surface orientation (Liu et al., 2018). Particle suspension or resuspension can also be affected by various factors, including particle size, relative humidity (RH), and air flow velocity.

HVAC systems are typically designed specific to the building and room in which they are installed, and therefore, it is difficult to make completely generalized claims about the type of system design and the resulting air quality. However, some general assumptions can be made based on basic and accepted air system models. As a general rule, centralized systems have the potential to provide the best dust and particulate control capabilities (Jung et al., 2015; Kochenkov et al., 2012). Most central systems can provide control over ventilation air and allow for fixed or varying quantities of fresh air (Kochenkov et al., 2012). In addition, because centralized systems operate from a single larger base system, central air systems have sufficient fan pressure to incorporate multi-stage filtration devices or even high efficiency particulate air (HEPA) filters (Kochenkov et al., 2012). Decentralized systems, while providing more control than natural ventilation, do not have the control capabilities of centralized systems, providing little to no flexibility on the control of fresh air intake. Additionally, decentralized systems cannot be modified to include the high level of filtration that central air systems can achieve due to fan pressure limitations (Kochenkov et al., 2012).

Many prior studies exist on aerosol deposition indoors (e.g., (Lai, 2002; Nazaroff, 2004)), and there is renewed interest in this work because of the pandemic (McNeill et al., 2022; Nafchi et al., 2021). A number of studies have indicated that there is still large uncertainty in accurately describing indoor aerosol deposition (e.g., (Diapouli et al., 2013)). Factors including ventilation type (Izadyar and Miller, 2022; Ratajczak, 2022; Zhao and Wu, 2009), forced-air stirring vs. calm, unstirred rooms (Schnell et al., 2006), furnishings (Abadie et al., 2001; Thatcher et al., 2002; Thatcher and Nazaroff, 1997), room or building geometry, intrusion of outside air to the
indoors (Bi et al., 2021; Han et al., 2022; Mohammadyan et al., 2017; Riley et al., 2002), and aerosol type (Alves et al., 2014; Lin et al., 2015) have all been considered with varying levels of agreement and understanding. Many of these studies have been done in idealized laboratory rooms in an attempt to reduce uncertainties and determine a model framework for describing aerosol deposition (Jamriska and Morawska, 2003). Many other studies have been performed in residential homes to gain a real-world understanding of aerosol deposition (e.g., (He et al., 2005; Howard-Reed et al., 2003)). Although several recent studies have been performed in classrooms, where ventilation systems in older buildings may be far from ideal and space and occupancy sizes are quite different than in any rooms in the homes we live in, there remains a need to build on our understanding of aerosol behaviour in these unique environments.

In this study, we performed experiments in several classrooms to assess the interaction between aerosols and different HVAC systems, classroom configurations, and exposure mitigation strategies. An examination of different HVAC systems is presented elsewhere (Nafchi et al., 2021). Here, we focus on results from a single classroom, the one in which the installed HVAC system performed worse in terms of improving indoor air quality. We altered the in-room fan speed and filter and added portable filtration technologies to study strategies for improving the indoor air quality of older, decentralized HVAC systems.

2 METHODS

2.1 Experimental Setup

Five classrooms on Clemson University’s main campus were selected to participate in the Ventilation and Aerosol DEcay Research (VADER) study during the summer of 2020 (Nafchi et al., 2021). The classrooms were selected primarily to represent a variety of ventilation types, but
they also represent a variety of sizes, layouts, and building ages. Table S1 in the Supplementary Information contains the list of each classroom tested and their information.

In this study, we focus our analysis on Classroom A (Fig. 1). Classroom A is a fairly typical classroom in a building of moderate age, built in 1958. The room is about 104 m² with about a 3 m tall drop ceiling and stated maximum occupancy of 68 people. The flooring is tile, there is a small wooden teaching podium at the front of the room, and the student desks are long countertops stretching across the room with a center aisle left open. There is no carpet or cloth material in most of the room; the exception is a small, raised platform at the front of the room.

HVAC control is accomplished by two fan coil units (FCUs) located on the outer wall with large windows to the outside. Each FCU brings in room air near the floor level, passes it through a Merv 8 filter layer, conditions the air by passing it over a heat exchanger, then expels the conditioned air out the top of the unit about 63.5 cm off the floor. Each FCU has a small vent to the outside, but these were in a closed position, and it is likely only a small leakage of outside air was entering the room. On the wall opposite the FCUs were two doors to the hallway and two small vents at ceiling level that vent to the space above the drop ceiling in the hallway next to the room. Our measurements recorded very little airflow through these vents, thus we assume that air within Classroom A does not mix or exchange with the outside or hallway air to any appreciable level, except when opening the doors. Airflow measurements at the vents were done with a TSI ALNOR EB-731 or a Proser handheld anemometer.

To conduct an experiment, a medical nebulizer (Allied Healthcare Aero Mist Nebulizer, model #ALH-61400) was used to create and release polydisperse aerosol particles (Bis-2-Ethylhexyl sebacate, CAS #122-62-3) into the air. In Classroom A, the particle release point (labelled “Source” in Fig. 1) was chosen right above one of the fan coil units to get maximum dispersion.
of particles in the room. Individual particle measuring units (Table 1) were strategically placed around the room (Fig. 1) to measure aerosol number concentration at specific points of interest (e.g., the teaching podium) and throughout the room. The particle counters measured particle concentration over time to assess the amount of time required to reduce the particle concentration by half, which will be referred to throughout this paper as the “particle concentration half-life.” Because the particle counters collected data at different time intervals, size bins, and raw data units, post-processing of the data converted the output from each device into number concentration of particles per cubic centimeter (cm$^{-3}$) to allow for a more direct comparison of all measurements. Table S2 in the Supplementary Information lists each experiment conducted in Classroom A during this study.

### 2.2 Data Analysis

After each particle release, particle concentration in the classroom was measured and recorded until the concentration either returned close to baseline levels or was no longer significantly decreasing. Fig. S1 in the Supplementary Information shows the particle concentration from consecutive particle releases in a single day of experiments. From our early experiments, it became clear that the overall baseline concentration of particles generally increased through a day of experiments, due either to our generation of particles in a size range that were never properly filtered by the HVAC system or by intrusion of outside air which contained a higher number concentration of aerosol later in the day. As we noted above, we did not directly measure any appreciable intrusion of outside air through the vents, but a potentially significant cause of air intrusion is the door openings as we entered and exited the room between each test (Bhattacharya et al., 2020).
To determine the decay rate and particle concentration half-life corresponding to each particle release and the varying conditions, the data from the particle measuring instruments were analyzed separately for each individual release. The release of the particles into the classroom resulted in a rapid spike of the concentration readings. Once no more particles were being released into the classroom, particle maximum concentrations were followed by a rapid decline in particle concentration readings. During the period directly following the particle release, the particle concentration in the room was poorly mixed, which resulted in increased variability between consecutive particle readings, often greater than a 10% difference between consecutive particle readings. After the percent difference between consecutive particle readings was less than 10% for several (three or more) readings, the subsequent data for the release was analyzed to determine the particle decay rate.

Fig. S2 in the Supplementary Information displays an individual particle release curve as well as its corresponding fitted exponential equation,

$$C - C_0 = (C_{peak} - C_0)e^{-\lambda t}$$  \hspace{1cm} (1)

where \(C\) is the instantaneous concentration, \(C_{peak}\) is the peak concentration following the initial release, \(C_0\) is the baseline or stable concentration before and after each experiment, and \(\lambda\) is the decay rate in \(s^{-1}\). From the decay rate established from the fitted curve, the particle concentration half-life \((T_{1/2})\) is found using Eq. (2),

$$T_{1/2} = \frac{\ln(2)}{\lambda}$$  \hspace{1cm} (2)

Baseline measurements were taken for approximately 10-15 minutes before the first release in the classroom. To avoid the effects of dissimilar baseline concentrations across all releases, the baseline concentration was deducted from concentration output of the particle measuring devices. For each additional consecutive test, the baseline concentration was calculated using the
decay equation established from the previous release at the start time of the release being analyzed. Once the decay rates and half-lives were established for each individual release, the effect of various conditions can be analyzed by comparing the changes to particle concentration half-lives in each experimental setup.

3 RESULTS AND DISCUSSION

3.1 Effect of Variations in Fan Speed

Classroom A relied solely on two fan coil units for ventilation (Fig. 1), which operate at three possible fan speeds: High, Low, and Off. The two fan coil units pull air in from the bottom of the unit (about 7.5 cm off the floor) and expel conditioned air out the vents on top of the unit (about 63.5 cm off the floor). Each fan coil unit contains a filter layer (MERV8) to trap large particles at the unit intake. Particle release tests were conducted in Classroom A while the fan coil units were set to various fan speeds to evaluate how the variation in air flow in the room would affect the filtration rate, expressed as the particle concentration half-lives.

In Classroom A, Fig. 2 shows that particle concentration half-lives were reduced for mCPC measurements of total aerosol concentration and for every particle size range measured by the VPC300s when the fan-coil units operated at the highest fan setting as compared to the lowest fan setting. At low fan speed, the average particle concentration half-lives ranged from 61 minutes for 0.3 µm aerosols to 30 minutes for 10 µm aerosols. At high fan speed, the average particle concentration half-lives ranged from 34 minutes for 0.3 µm aerosols to 22 minutes for 10 µm aerosols, a reduction in half-life time of 45% and 25%, respectively. These results indicate that the change in fan setting from low to high had a larger impact on particles less than 1 micron in diameter. Below 1 µm, the percent difference between the particle concentration half-lives based on the change in fan speed was above 40%. For the larger particle sizes, the percent
difference in particle half-lives was reduced by 39%, 30%, and 25%, respectively, for 2.5 µm, 5 µm, and 10 µm diameter aerosol. The trend in these data, showing a decreasing relative improvement in particle removal at the larger sizes, likely indicates that processes other than filtration become important at the larger particle sizes, as discussed below.

Fig. 2 also shows the case when both fan coil units were turned off which, in most cases, displays a much longer particle concentration half-life time than when the FCUs are on at any speed. Note that we were only able to perform one Fans Off experiment and that the particle concentration decay was so small that there was considerable noise in the data, which led to exponential fits with Eq. (1) that had low coefficients of determination (about 0.4 – 0.7 for most measurements). With the fans off, random air currents in the room also contributed to variable particle concentrations that did not always monotonically decrease with time. Overall, particles are still removed from the air by mechanisms other than filtration, but the process is significantly slower, as expected. Other particle removal mechanisms to consider include aerosol motion by air currents leading to impaction on surfaces, gravitational settling, deposition by diffusion, and particle coagulation.

The gravitational settling time can be estimated using the terminal settling velocity, \( V_t \), calculated as a function of particle size using the properties of the particle material and room conditions (e.g., temperature and pressure) and accounting for slip correction factor for smaller particle sizes (Hinds, 1999). To estimate the effect on particle concentration in the room, additional assumptions that the room is well-mixed and there are no appreciable air currents to keep particles suspended must be made. Then, one can solve for the number concentration as a function of time using Eq. (3),
\[ n(t) = n_0 e^{-\left(\frac{V}{H}t\right)} \]  

where \( n_0 \) is the initial concentration, \( H \) is the room height, and \( t \) is time. To compare to the particle concentration half-lives determined from experimental data, set \( n(t)/n_0 \) equal to 0.5 and solve for the time, \( t \). The resulting calculations indicate that for gravity settling alone with the above assumptions, particle concentration half-lives would be well over 1,000 minutes for particles 1 µm in diameter and smaller, and about 192, 40, and 13 minutes for 2.5 µm, 5 µm, and 10 µm diameter aerosol, respectively. Although this calculation has obvious limitations because of the assumptions we needed to make (i.e., that there are no air currents, the room is completely well-mixed at all times, and that all particles fall from a height equal to the room height), that the gravity settling times alone are close to the half-lives indicated by the data for 5 and 10 µm diameter aerosol for all fan speeds (Fig. 2) indicates the importance of this process in removing the larger particles from the air.

Smaller particles are much less influenced by gravitational settling, and instead, are more affected by deposition onto surfaces by diffusion. However, even at a particle diameter of 0.1 µm, diffusional deposition is only about 3 times more effective than gravitational settling (Hinds, 1999). Diffusion becomes much more important at even smaller aerosol sizes, likely below the detection limit of all instruments used in this study except for the mCPC. Because the initial particle concentration for any experiment in this study never exceeded \( 10^4 \) cm\(^{-3} \), aerosol coagulation is ignored as a potential removal mechanism, following convention (Hinds, 1999; Lai, 2002). Other aerosol effects, such as particle evaporation and condensation, can be neglected in this study as well because the material nebulized for these experiments is a non-volatile, inert, and oily substance. Therefore, the data presented in Fig. 2 is primarily illustrating the increased filtration capacity of the FCUs owing to the fan speed settings.
A common metric used to describe the rate of aerosol deposition indoors is the particle deposition velocity, $V_d$ (Lai, 2002). Although a direct measurement of particle flux to surfaces in Classroom A was beyond the scope of our study, an approximation known as the area-weighted average deposition velocity, $\overline{V_d}$, can be calculated from the decay rate, $\lambda$, using Eq. (4),

$$\overline{V_d} = \lambda \frac{V}{\sum A}$$

where $V$ is the volume of the room (317 m$^3$) and $A$ is the deposition area within the room (335 m$^2$). For this analysis, we did not attempt to quantify the surface area of furnishings in the room; thus, $A$ represents just the walls, floor, and ceiling of the room. For the data displayed in Fig. 2, the corresponding $\overline{V_d}$ when the FCU is on low fan speed ranges from $1.78 \times 10^{-4}$ m s$^{-1}$ for the 0.3 µm size bin up to $3.64 \times 10^{-4}$ m s$^{-1}$ for the 10 µm size bin. At the high fan speed setting, the $\overline{V_d}$ ranges from $3.25 \times 10^{-4}$ m s$^{-1}$ for the 0.3 µm size bin up to $4.90 \times 10^{-4}$ m s$^{-1}$ for the 10 µm size bin. These area-weighted average deposition velocities are consistent with other studies of room-sized chambers, as summarized by Lai (2002).

Our results are consistent with other studies and are not particularly surprising, increasing the air flow and, thus, ventilation and filtration rate in the classroom reduces the amount of time that particles are suspended in the air. In Classroom A, because the fan coil units draw in air from the classroom and do not mix with air external to the classroom or building, increasing the fan coil output air volume directly increases the volume of classroom air passing through the filter, which allows more particles to contact the filter. When considering steps to take to improve the indoor air quality in this classroom, the simplest solution would be to run the existing ventilation system at a higher fan speed. This solution is not always practical in teaching classrooms, however, if, for example, the FCU is older and has a louder operating fan.
3.2 Mitigation Strategies

Portable and low-cost mitigation strategies were employed in Classroom A to evaluate their effect on particle concentration half-lives. In this study, three variations of mitigation strategies representing both high- and low-cost solutions were evaluated, as summarized in Table 2. The fan coil units in Classroom A normally operate with a single MERV8 filter layer installed. The first mitigation strategy tested in Classroom A was the simple addition of a second MERV8 foam filter layer installed in each fan coil unit on top the of existing filter layer. To simulate this strategy as the possible lowest-cost method to reduce indoor air exposures, no other modifications to the fan coil units were done. While it is possible that a poor seal around the FCU could allow leakage that would effectively bypass the filters, our installation of a second layer was unlikely to significantly change the existing seal; thus, we have confidence that air flowed through the second filter layer in these experiments in a similar manner to the single layer experiments. Fig. 3 compares the particle concentration half-lives for an experiment with one and two filter layers and high fan speed with those from an experiment with a single filter layer and low speed. The addition of a second filter layer reduced the particle concentration half-lives for the smaller particle size bins measured by the VPC300s, specifically reducing the 0.3 and 0.5 µm particle concentration half-lives by 61% and 47%, respectively. A two-sample \( t \)-test at a 5% significance level reveals that the datasets for the 0.3, 0.5, and 1 µm size bins are statistically different (\( p \)-values of 0.0065, 0.0089, and 0.0292, respectively), while data at the large size bins are not. Also, while there were multiple VPC300 instruments allowing for a larger population of measurements for each experiment, there was only one mCPC resulting in fewer measurements, particularly for the two-filter layer experiments. Thus, where it looks like the two filter layers performed worse than a single filter layer in Fig. 3, the data appear this way more due to the lack
of repeated measurements than representing any actual particle removal phenomenon. It is worth noting that the velocity of air through the FCUs was reduced from an average of about 2.1 m s\(^{-1}\) to 1.8 m s\(^{-1}\) owing to the increased pressure drop from two filter layers as opposed to one.

The second strategy to mitigate potential exposure to indoor PM was to employ a portable, higher-cost HEPA filtration unit, which can theoretically remove 99.97% of 0.3-micron particles (EPA, 2021). The RabbitAir model is recommended by the manufacturer to provide standard coverage for rooms that are 815 square feet (about 76 m\(^2\)), and the unit has a maximum air flow volume of 218 CFM (RabbitAir, 2021). The third mitigation strategy utilized a low-cost filtration device constructed using a standard 20-inch box fan and a MERV13 air filter. The MERV13 air filter was attached to the box fan intake side and the edges sealed with tape (see Fig. S3). In a repeat experiment, the box fan was slightly modified by adding more tape (see Fig. S4), but the results were statistically similar between the two configurations and thus were averaged together in the data presented in Fig. 4. When either portable filter unit was employed, the FCUs operated on high fan speed with a single filter layer.

Fig. 4 shows that when either portable filtration device was deployed in Classroom A, particle concentration half-lives decreased significantly as compared to only operating the fan coil units on high speed. The average particle concentration half-lives ranged from about 34 minutes at 0.3\(\mu\)m to 22 minutes at 10\(\mu\)m when the fans were set to high speed with no portable mitigation devices in Classroom A. When the HEPA filtration device was employed during the particle release tests, average particle concentration half-lives decreased to about 16 minutes at 0.3\(\mu\)m and 13 minutes at 10\(\mu\)m, a reduction of about 53% and 41%, respectively. When the box fan with filter was deployed during the particle release tests, average particle concentration half-lives ranged from about 17 minutes at 0.3\(\mu\)m to 13 minutes at 10\(\mu\)m, a reduction of about 50% and
Although the box fan with filter appears to underperform the HEPA filter only slightly over the VPC300 size bins, note that these two datasets are not statistically different from each other; two-sample $t$-test $p$-values at a 5% significance level are 0.39, 0.29, 0.88, 0.74, 0.50, and 0.15, respectively, for the size bins from 0.3 to 10 µm. The mCPC data do show more separation in performance between the box fan and the HEPA filter, but these are still not statistically different data ($p$-value is 0.15). This performance is consistent with the fact that the mCPC is able to detect particles much smaller than the VPC300 instruments can. These particles are easily removed from the air by the HEPA filter and, thus, a dramatic change in particle concentration half-life is likely. However, as we noted earlier, there are fewer repeat measurements for the mCPC, meaning that the datasets are prone to large errors with so few measurements. More repeat experiments are needed to further test whether there are any real differences between HEPA and box fan mitigation methods in this study.

Our results indicate that the low-cost box fan with filter performed similar to the higher-cost HEPA filter. While the HEPA filtration unit has, theoretically, the best particle removal efficiency against all particle size ranges, the low-cost unit is likely able to pass a much greater volume of air through its filter for the duration of the particle release tests and, thus, can compete with the HEPA filter for overall removal of particles from the air. The HEPA unit utilized in this study has a maximum flow rate of 218 CFM, while an average 20-in box fan can pull an estimated 1000-2500 CFM without the filter attached (McWhirter, 2020).

Air changes per hour (ACH) is typically calculated for a given room as the total volumetric flow rate through an HVAC system into that room divided by the room’s volume (McNeill et al., 2022). In this study, Classroom A has only fan coil units in the room, thus, the ACH of the room was simply how many times per hour the room air passed through the FCU and therefore through...
the MERV8 filter. To compare our experiments including the portable filter units on a common scale, we added the flowrate from the portable filtration units to the FCU supply air rate for Classroom A to calculate an overall ACH for display in Fig. 5. Because ACH is typically used to compare multiple rooms and filtration setups, Fig. 5 also includes particle concentration half-life data from the other classrooms in the overall study (Nafchi et al., 2021).

Fig. 5 shows that when comparing different classrooms, and therefore different HVAC units, one observes an overall decreasing trend in particle concentration half-lives with increasing ACH. One major exception is Classroom E, in which we suspect the calculated ACH value is incorrect owing to vent locations in the room that were hard to reach and, thus, we were unable to ensure accurate airflow measurements. It is likely that each classroom had a MERV8 air filter installed in their air handling units, regardless of HVAC type, though we were not able to independently confirm each installation. Nonetheless, we expect that the filtration process is likely similar in each room, and the reduction in particle half-lives is, therefore, related to the number of times the air passes through the filters.

The second major observation from Fig. 5 is the effect of the portable filter units added to Classroom A. Both units clearly reduced the particle concentration half-life from the base values (FCU on Low and FCU on High). The box fan filter result is at a higher ACH value owing to its higher volumetric flow rate as compared to the HEPA filter. Despite having a much lower ACH, and therefore having a lower volume of air contacting the filter, the HEPA filter result produces a particle concentration half-life nearly as low as other classrooms with much higher ACH values. This result makes sense because the HEPA filtration unit has a much higher filtration efficiency than the other filters used in this experiment, and therefore, it is reducing particle concentration half-lives more significantly than the other filters at any given ACH value. While
the low-cost option shows promise as a more affordable, yet still effective method of removing particles and improving air quality in a classroom setting, a major disadvantage to utilizing the low-cost option is the increased noise levels from the unit as compared to the quieter HEPA unit. Although we did not quantify noise level, qualitatively we observed a noticeable difference in the two units; the HEPA unit was only audible when standing very close to the unit while the box fan could be heard from anywhere in the room. Here, we only tested the highest (and loudest) setting on the box fan to measure the maximum effects of that unit; in reality, one of the lower fan speed settings may produce a tolerable noise level and yet still be effective at improving indoor air quality.

3.3 Exposure Analysis

An additional objective of the particle release tests was to apply the decay rates and particle concentration half-lives to further understand potential exposure risks to airborne pathogens in a university classroom setting. However, it is important to note the limitations of an exposure analysis in this context. No viral particles or data from actual infected individuals were utilized or obtained during this study. This experiment was designed to collect data on particle behaviours in various classroom settings with different HVAC configurations and portable mitigation strategies. We can apply the particle concentration half-lives found in this study to help answer the question, “if an individual, infected with a viral pathogen, was present in Classroom A during a 60-minute class period, what would be the potential exposure to other classmates?”

Understanding how a virus spreads and its infectivity is a crucial step in determining health guidelines and exposure limits. Here, we perform an example calculation of how one might use the particle concentration decay data presented above. The relevant metric to calculate here is
infectious dose, or the amount of virus necessary to make a person sick. As an example, the human infectious dose of the influenza A virus, when administered by aerosol, ranges between $1.95 \times 10^3$ and $3.0 \times 10^3$ viral particles (Nikitin et al., 2014). While the minimum infectious dose of SARS-CoV-2 is still unknown, and likely varies greatly between different variants, researchers suspect it is low, with some estimating the minimum infectious dose of COVID-19 as low as 100 viral particles (Karimzadeh et al., 2020; Schröder, 2020). Eq. (5) shows the generic equation for total dose ($D_T$), where $CR$ is the contact rate, $C$ is the concentration of contaminant, $BW$ is body weight, and $t_e$ is the time of exposure.

$$D_T = \frac{CR}{BW} \int_0^{t_e} C(t) dt$$ (5)

Because we are considering here a university classroom, the contact rate will be represented by the inhalation rate of an average adult. According to the EPA Exposure Factors Handbook, for adults not engaged in physical activity, the average inhalation rate is $16 \, \text{m}^3/\text{d}$ or $0.67 \, \text{m}^3/\text{hr}$ (EPA, 2011a). The average body weight for adults is $80 \, \text{kg}$ (EPA, 2011b). The time of exposure will be set at 60 minutes, or approximately the length of one class period, and the particle decay rate from the particle release experiment will be utilized to calculate the concentration of viral particles using Eq. (6), where $C_{\text{peak}}$ is the initial concentration of contaminant, $\lambda$ is decay constant, $t_e$ is the time of exposure:

$$C(t) = C_{\text{peak}}e^{-\lambda t_e}$$ (6)

The last crucial piece of information required is the initial concentration of the pathogen. Human activities such as coughing, sneezing, speaking, and even breathing generate respiratory particles, which may contain live viruses (Gralton et al., 2013; Hawks et al., 2021; Stadnytskyi et al., 2021; Thacher and Mäkiharju, 2022).
Coughing is an important mechanism in respiratory clearance, as well as the most common symptom of many infectious respiratory diseases (Zayas et al., 2012). Sneezing is also an important pathway because sneezes result in a larger number of respiratory droplets that are expelled at a higher velocity, and thus can travel farther distances (Dhand and Li, 2020; Salati et al., 2022). While the number of droplets produced by the various activities (coughing, sneezing, etc.) varies based on many individual factors, we will assume that a cough will be able to produce approximately 10,000 respiratory droplets, and a single sneeze can release an estimated 40,000 respiratory droplets (Dhand and Li, 2020; Lindsley et al., 2012; Zayas et al., 2012).

Another critical assumption required to apply the exposure calculation is that the room is well mixed, and that after the particle release (by sneeze, cough, etc.) all locations in the room have identical concentrations and trends. We know that this assumption is not entirely true, as the concentration readings differed during the experiments across particle counters, indicating the room was not completely well-mixed (Nafchi et al., 2021). This assumption makes the following calculation an average value, but without knowing the details of the mixing, there are likely a widely varying level of exposures throughout the classroom.

Fig. 6 displays the resulting total dose, given as cumulative number of viral particles inhaled during the 60-minute exposure time. In Classroom A, having the fan coil units set to the high fan setting resulted in a 22% reduction of total estimated viral particles inhaled from a single sneeze as compared to on the low fan setting, and including a HEPA filtration unit in the room resulted in a 66% reduction of total estimated viral particles inhaled from a sneeze as compared to on the low fan setting. Although the total dose number seems small, note that this calculation was based on a single sneeze event. Perhaps in a real scenario, an individual would be exposed to multiple sneezes and coughs, in addition to particles expelled during normal breathing, during a 60-
minute class period. Also, given the uncertain mixing in Classroom A, it is likely that some areas of the room would experience a higher dose than the average values displayed in Fig. 6. A real-world scenario would be much more complicated than our simple calculation here, but this example demonstrates the effectiveness of mitigation strategies to reduce potential exposures.

As described in previous sections, increasing the air flow through the fan coil units reduces the amount of time the particles are suspended in the air by increasing the volume of classroom air passing through the particle filter, and introducing a portable filtration device such as a HEPA filter will reduce particle concentration half-lives even further. Therefore, introducing measures such as higher ventilation rates and portable mitigation devices reduces the total dose of viral particles inhaled by ensuring that particles are suspended in the air for shorter time periods.

4 CONCLUSIONS

Variations in ventilation configuration alter particle behaviour and thus change airborne particle concentration half-lives. In classrooms with decentralized ventilation systems, increasing air flow rates by increasing the fan speed of individual fan coil units reduced particle concentration half-lives. Half-lives of smaller particle size bins were more significantly reduced than those of larger particles, likely due to the larger particles being more affected by gravitational settling than filtration. Increasing the air changes per hour, whether by increasing the output of decentralized units or by using portable filtration devices, generally resulted in reduced particle concentration half-lives, consistent with the literature. An exception to this rule is when the filtration efficiency is significantly different between setups, such as is the case with a portable HEPA filter unit. The HEPA filter used in this study did not significantly increase the ACH in the room but did significantly reduce the particle concentration half-life (i.e., increased the
One goal of this study is to apply the results and findings on particle behaviour to further our understanding of airborne pathogen transmission between indoor occupants in the same classroom. The example calculation presented here indicates that running the fan coil unit fan speed on high instead of low results in a 22% reduction in potential exposure to harmful particles, and use of a portable HEPA filter in the room results in a 66% reduction in potential exposure.

Future work will include investigating the effects of different spatial locations within a classroom, including placement of the portable filtration devices within the room. More coverage by many more particle sensors is necessary to capture the intricate details of air motion in rooms. This research could also be expanded to include additional classroom experimental setup scenarios, such as classrooms that have no ventilation options, or that exclusively use natural ventilation (i.e., open windows). When translating the aerosol decay rates into potential exposures for individuals in the room, a more detailed model of the many aerosol processes occurring in the room is necessary.

**ACKNOWLEDGEMENTS**

We gratefully acknowledge the Clemson University Facilities departments for providing access to classrooms during the height of the pandemic and for providing additional HVAC filters and a portable HEPA filter for testing.

**DISCLAIMER**

Reference to any companies or specific commercial products does not constitute an endorsement.
REFERENCES


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Table 1 - Particle Measuring Devices

<table>
<thead>
<tr>
<th>Make</th>
<th>Model</th>
<th>Measurement Type</th>
<th>Measurement Interval</th>
<th>Particle Size Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRECHTEL</td>
<td>MCPC 1720</td>
<td>Particles/cm³ (sample rate 0.36 L/min)</td>
<td>1 second</td>
<td>7-2000 nm (0.007-2 µm)</td>
</tr>
<tr>
<td>EXTECH</td>
<td>VPC300</td>
<td>Particles per intake (sample rate 2.83 L/min)</td>
<td>15 second intake with 15 second interval</td>
<td>0.3, 0.5, 1.0, 2.5, 5.0, 10 µm</td>
</tr>
<tr>
<td>DYLOS</td>
<td>DC1100</td>
<td>Particles/ft³ (sample rate 0.28 L/min)</td>
<td>60 seconds</td>
<td>Small: &lt;5 µm Large: &gt;5 µm</td>
</tr>
</tbody>
</table>
### Table 2 - Mitigation Strategies

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Device</th>
<th>Cost</th>
<th>Filter Efficiency per Particle Size&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HEPA Filter</strong></td>
<td>RabbitAir Minus2A SPA 780A</td>
<td>Higher-cost</td>
<td>0.3 µm = 99.97%; &lt;0.1 µm = &gt;99%</td>
</tr>
<tr>
<td><strong>MERV13 Filter</strong></td>
<td>Box fan - Modified</td>
<td>Low-cost</td>
<td>1.0 - 3.0 µm = 80-89.9%; 3.0 - 10.0 µm = &gt;90%</td>
</tr>
<tr>
<td><strong>MERV13 Filter</strong></td>
<td>Box fan - Unmodified</td>
<td>Low-cost</td>
<td>1.0 - 3.0 µm = 80-89.9%; 3.0 - 10.0 µm = &gt;90%</td>
</tr>
<tr>
<td><strong>MERV8</strong></td>
<td>Fan Coil Unit Filter</td>
<td>Low-cost</td>
<td>3.0 - 10.0 = 84.9%</td>
</tr>
</tbody>
</table>

<sup>a</sup>https://www.epa.gov/indoor-air-quality-iaq/what-hepa-filter-1, (EPA, 2021)
Figure 1 - Layout and equipment setup for Classroom A. The stated flow rates for the FCUs are the maximum rates; these were varied during this study. The “Source” is the location of the particle releases.
Figure 2: Particle concentration half-life for the mCPC and VPC300 size bins, separated based on fan speed. Error bars represent the sample standard deviation across repeated particle release events. Note that the Fans Off data do not include error bars because we conducted this experiment only once during this study.
Figure 3 – Particle concentration half-lives for the mCPC and VPC300 size bins, separated based on fan speed and number of filter layers in the FCU. Error bars represent the sample standard deviation across repeated particle release events and multiple measurement points in the room. Note that not all experiments were repeated the same number of times, and the Fans on Low experiment had one filter layer in the FCU.
Figure 4: Particle concentration half-lives for the mCPC and VPC300 size bins, separated based on FCU fan speed or various mitigation devices employed. Error bars represent the sample standard deviation across repeated particle release events and multiple measurement points in the room. Note that not all experiments were repeated the same number of times.
Figure 5 Average particle concentration half-life for 0.3-micron particles as a function of the calculated air changes per hour. Circles represent datapoints from Classroom A, as described in the text. Squares represent datapoints from the other Classrooms in the larger study described by Nafchi et al., 2021. Error bars indicate the standard deviation of multiple experiments, where applicable. For the Box Fan, the x-axis error bar indicates the spread in uncertainty owing to the unknown box fan speed.
Figure 6 - Variations in potential dose of inhaled viral particle during different ventilation setups.