An Experimentally Validated Analytical Model for Aerosol Number Concentration Reduction in Classrooms

Qingfeng Cao¹, Thomas H. Kuehn¹, Seong Chan Kim¹, Qisheng Ou¹, Chenxing Pei¹, David Y.H. Pui¹²*

¹ Department of Mechanical Engineering, University of Minnesota, 111 Church Street SE, Minneapolis, Minnesota 55455, USA
² School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen, Guangdong 518172, China

ABSTRACT

To predict the aerosol number concentration decay in modern classrooms, this study derived an analytical model that addresses various indoor factors, viz., the filtration efficiency of air ventilation systems, effects of indoor air cleaners, particle deposition on walls, and particle emission from occupants. We also conducted experimental measurements to determine the wall-loss coefficient and the occupants’ particle generation rate, and the modeling results agreed with the experimental data reasonably well. Additionally, we investigated the behavior of the particle concentration decay in different ventilation scenarios. The model has been incorporated into web-based software that is freely available to the public.

Keywords: Analytical model, Aerosol concentration, Classrooms, Ventilation system, Indoor air quality, COVID-19

1 INTRODUCTION

The coronavirus 2019 (COVID-19) pandemic has resulted in severe disruption to the economy and social activities and caused coronavirus disease for millions of patients worldwide (Bartik et al., 2020; Donthu and Gustafsson, 2020; Mehta et al., 2020; Nicola et al., 2020; Shereen et al., 2020; Zheng et al., 2020). With schools and universities reopening in September 2020 in the United States, the potential airborne transmission of COVID-19 in classrooms has raised significant concerns regarding the safety of students and teachers during classes. Studies have found that the transmission of COVID-19 has a relation to indoor ambient aerosols (Amirav and Newhouse, 2020; Asadi et al., 2020; Mehmood et al., 2020; van Doremalen et al., 2020). Therefore, ventilation systems play a key role in controlling coronavirus spreading in the classrooms, dental clinics, hospitals, etc. by keeping the indoor infectious virus aerosol concentration at a minimal level. This study aims to develop an analytical model for the particle number concentration decay under different operational conditions of ventilation systems in modern classrooms, which will be beneficial for minimizing the indoor airborne transmission of COVID-19.

Many researchers have conducted investigations on indoor air quality in classrooms. A major group of studies were focused on the indoor-outdoor correlations of particle number concentrations for classrooms under different ventilation situations (Tippayawong and Khuntong, 2007; Guo et al., 2008; Mullen et al., 2011; Fuoco et al., 2015; Ren et al., 2020). They found that air exchange rate and outdoor contaminant concentrations have a significant impact on classroom particle concentrations. In addition, the effect of ventilations systems on indoor air quality was evaluated through numerous experimental and numerical investigations, and different ventilation strategies were studied and suggested for better controlling the indoor concentration levels (Holmberg and
Chen, 2003; Howard-Reed et al., 2003; Park et al., 2008; Tian et al., 2009; Stabile et al., 2016; Johnson et al., 2018; Stabile et al., 2019). Weichenthal et al. (2008) characterized the ultrafine particle levels in Canadian classrooms and developed a model to predict the ultrafine particle concentrations based on the weather conditions, outdoor particle concentrations and classroom conditions. Generation rates from diverse sources and removal rates by deposition and air exchange processes of ultrafine particles in classrooms were quantified by Laiman et al. (2014). Fazli et al. (2019) evaluated the size-resolved removal efficiency of various new commercially available HVAC filters for ultrafine particles, which can be applied in the ventilation systems of schools and universities. Investigators have also previously conducted size-resolved concentration measurements on biological aerosols in classrooms under occupied and vacant conditions to study the influence of occupant emissions on indoor air quality (Qian et al., 2012; Bhangar et al., 2014). The impact of occupants’ activities on aerosol emissions and source of contaminants in classrooms were also examined by several experimental researchers (Alshitawi and Awbi, 2011; Bennett et al., 2019; Kim et al., 2019).

Over the years, various analytical and numerical models have been developed for the purpose of predicting the indoor air quality under different situations. Well-mixed models have been around for several decades, and local mean age and ventilation effectiveness were introduced in the 1970s to expand beyond the limitation of assuming perfect mixing (Kuehn et al., 1998). Nazaroff and Cass (1989) presented a mathematical framework for particle concentrations in indoor air, which considered the effects of ventilation, filtration, surface deposition, emission, and coagulation. The study by Pui et al. (2008) indicated that airborne nanoparticle concentrations were significantly diminished by recirculation air filtration, and an analytical model was developed to account for the particle concentration change in a closed space. Adeniran et al. (2019) performed analytical modeling for human exposure to aerosols as a function of time and distance, which describes point source dispersion and concentration decay that resulted from air exchange rate and particle deposition. Ganesh et al. (2019) developed an analytical model to predict the concentration of different kinds of indoor pollutants, which takes contaminants from an Air Handling Unit (AHU) and indoor emission sources into consideration. On the other hand, researchers have carried out numerical simulations by using computational fluid dynamics approaches to explore the physics of particle dispersion, deposition, transportation, emission, and interactions with occupants and indoor airflow fields (Holmberg and Li, 1998; Sajjadi et al., 2017; Liu et al., 2019; Nsir et al., 2019; Borro et al., 2020; Mutlu, 2020; Vuorinen et al., 2020). With the drastic advancement in the computer-science-related fields in recent years, techniques such as artificial neural network and machine learning have also been applied to predict indoor air quality (Gheziehl et al., 2017; Wei et al., 2019). Nowadays, a modern classroom can be serviced by both an AHU and a Fan Coil Unit (FCU) with Indoor Air Cleaners (IACs) sometimes applied to control the indoor air quality as well. Nevertheless, there has not been a comprehensive analytical model that includes the particulate filtration efficiencies of all these modern ventilation systems and indoor air cleaners together with other effects including particle absorption on walls and particle emission from occupants.

In this paper, the derivation of the analytical model based on modern configurations of ventilation systems for classrooms is first presented, followed by introducing the method of determining the empirical parameters for the wall-loss coefficient and particle generation rate per occupant. Comparison between the analytical model and experimental data is then analyzed. In “Results,” scenarios of indoor particle concentration decay with different ventilation conditions are presented and discussed.

2 DERIVATION OF THE ANALYTICAL MODEL

Fig. 1 presents the schematic diagram of the flow system in a classroom studied at the University of Minnesota. The ventilation system is composed of an AHU and an FCU, which are devices to regulate and circulate air as part of the heating, ventilating, and air-conditioning (HVAC) system for a modern classroom. The AHU introduces clean air into the classroom by blowing the outdoor ambient air through its filters, while the FCU functions by recirculating the room air through its filtration system. IACs have also been considered in the derivation. If we assume that the room air is perfectly mixed at all times, the governing equation describing the rate of indoor particle
Fig. 1. A schematic diagram of the flow system in the studied classroom.

The number change with time can be written as:

\[
V \frac{dN_{dp}}{dt} = Q_{AHU} \left(1 - \eta_{AHU,dp}\right)N_{a,dp} - \left(Q_{AHU} + \eta_{FCU,dp}Q_{FCU} + \eta_{IAC,dp}Q_{IAC} + A_i k_{w,dp}\right)N_{dp}(t) + S_{dp}
\]  

(1)

where \(V\) is the total volume of the classroom, \(t\) is time, and \(Q_{AHU}, Q_{FCU}, \text{ and } Q_{IAC}\) represent the airflow rates of the AHU, FCU, and IAC, respectively. The particulate filtration efficiencies of these three systems are functions of particle size and are designated as \(\eta_{AHU,dp}, \eta_{FCU,dp}, \text{ and } \eta_{IAC,dp}\), respectively. The number concentration of a specific particle size in the room is given as \(N_{dp}\) and the outdoor ambient concentration by \(N_{a,dp}\). The indoor particle emission rate is given as \(S_{dp}\), with \(A_i\) and \(k_{w,dp}\) representing the internal surface area of the classroom and the wall-loss coefficient, respectively.

Eq. (1) is valid for a specific particle size. However, we are interested in results that encompass a range of sizes. Each term in Eq. (1) is integrated over a particle size range, \(dp = m - n\), that results in the following equation:

\[
V \frac{dN(t)}{dt} = Q_{AHU} \left(1 - \eta_{AHU}\right)N_{a} - \left(Q_{AHU} + \eta_{FCU}Q_{FCU} + \eta_{IAC}Q_{IAC} + A_i k_{w}\right)N(t) + S
\]  

(2)

where the terms are no longer directly functions of particle size but depend on the particle size range selected for the integration. The particle size limits used here are 2.5 nm and 2 \(\mu\)m, which correspond to the range of the measuring instruments used in the corresponding experiments.

To obtain an analytical solution of Eq. (2), we first need to rewrite the equation into the following formats of:

\[
dN(t) = \frac{1}{N(t) - \frac{S + Q_{AHU} \left(1 - \eta_{AHU}\right)N_a}{Q_{AHU} + \eta_{FCU}Q_{FCU} + \eta_{IAC}Q_{IAC} + A_i k_{w}}} \frac{Q_{AHU} + \eta_{FCU}Q_{FCU} + \eta_{IAC}Q_{IAC} + A_i k_{w}}{V} \frac{dN(t)}{dt}
\]  

(3)

and:

\[
d\left[\ln\left(N(t) - \frac{S + Q_{AHU} \left(1 - \eta_{AHU}\right)N_a}{Q_{AHU} + \eta_{FCU}Q_{FCU} + \eta_{IAC}Q_{IAC} + A_i k_{w}}\right)\right] = \frac{Q_{AHU} + \eta_{FCU}Q_{FCU} + \eta_{IAC}Q_{IAC} + A_i k_{w}}{V} dt
\]  

(4)

By integrating both sides of Eq. (4), the following equation can be obtained:
\[
\ln \left( N(t) - \frac{S + Q_{AHU} (1 - \eta_{AHU}) N_0}{Q_{AHU} + \eta_{FCU} Q_{FCU} + \eta_{IAC} Q_{IAC} + A_s k_w} \right) = \frac{-Q_{AHU} + \eta_{FCU} Q_{FCU} + \eta_{IAC} Q_{IAC} + A_s k_w}{V} \cdot t + M \tag{5}
\]

where \( M \) is the coefficient generated during the integration. Eq. (5) can be further rewritten as:

\[
N(t) = a \cdot e^{\left( \frac{-Q_{AHU} + \eta_{FCU} Q_{FCU} + \eta_{IAC} Q_{IAC} + A_s k_w}{V} \right) t} + \frac{S + Q_{AHU} (1 - \eta_{AHU}) N_0}{Q_{AHU} + \eta_{FCU} Q_{FCU} + \eta_{IAC} Q_{IAC} + A_s k_w} \tag{6}
\]

where \( a \) is a coefficient equal to \( e^M \). We assume that initially the classroom is well mixed with a particle number concentration of \( N_0 \). This initial condition is applied to Eq. (6) so that we are able to find the coefficient of \( a \):

\[
a = N_0 - \frac{S + Q_{AHU} (1 - \eta_{AHU}) N_0}{Q_{AHU} + \eta_{FCU} Q_{FCU} + \eta_{IAC} Q_{IAC} + A_s k_w} \tag{7}
\]

By substituting Eq. (7) into Eq. (6), the final form of the analytical solution of Eq. (2) is written as:

\[
N(t) = \left( N_0 - \frac{S + Q_{AHU} (1 - \eta_{AHU}) N_0}{Q_{AHU} + \eta_{FCU} Q_{FCU} + \eta_{IAC} Q_{IAC} + A_s k_w} \right) \cdot e^{\left( \frac{-Q_{AHU} + \eta_{FCU} Q_{FCU} + \eta_{IAC} Q_{IAC} + A_s k_w}{V} \right) t} + \frac{S + Q_{AHU} (1 - \eta_{AHU}) N_0}{Q_{AHU} + \eta_{FCU} Q_{FCU} + \eta_{IAC} Q_{IAC} + A_s k_w} \tag{8}
\]

The above equation describes the particle number concentration change as a function of time. This equation can be applied to any specific airborne contaminant, including gases.

3 DETERMINATION OF THE WALL-LOSS COEFFICIENT AND OCCUPANTS’ PARTICLE GENERATION RATE

To apply Eq. (8), the empirical parameter, the wall-loss coefficient, \( k_w \), should be determined first. This parameter accounts for the absorption effect of walls on indoor contaminants in the classroom (Crump and Seinfeld, 1981; Crump et al., 1983; Fotou and Pratsinis, 1993). To obtain \( k_w \), experimental measurements were carried out by shutting off all the air-cleaning devices, including the AHU, FCU and IAC, so that a natural decay of the indoor particle concentration was achieved. A classroom on the fourth floor of the Department of Mechanical Engineering at the University of Minnesota was selected for the experiments, which has dimensions of 2.65 m, 10.25 m, and 6.83 m in height, length, and width, respectively. Thus, the total volume, \( V \), and internal surface area, \( A_s \), were calculated to be 185.80 m\(^3\) and 230.65 m\(^2\), respectively. NaCl particles were generated by an atomizer with a 1% solution to fill the room with an initial particle concentration of 23,500 \#/cm\(^3\), after which the atomizer was turned off and the particle concentration was allowed to decay naturally. The decreasing concentration was monitored by a condensation particle counter (CPC Model 3756; TSI Inc.), which is able to count ultrafine particles with a size range of 2.5 nm–2 \(\mu\)m, over the next 60-min period. As shown by the dotted curve in Fig. 2, the particle concentration decreased by 48% in 1 h. By fitting the measurement data with Eq. (8), the wall-loss coefficient, \( k_w \), was found to be \(1.71 \times 10^{-4} \text{ m s}^{-1} \). The fitted curve is presented in black in the figure, with an \( R^2 \) value equal to 0.940. Note that the classroom used for the experiment was not empty, but contained several tables and chairs, which added additional surface area for particle deposition. It would be difficult for the model to account for the additional surface area precisely due to indoor furniture and furniture settings in different classrooms could vary. However, the authors believe that the present results are valid for typical classroom settings. The effect of furniture surface area on indoor particle deposition is an interesting topic for a future study.
The term $S$ in Eq. (8) represents the emission rate of all indoor particle sources. During the experimental measurements, eight occupants were brought into the classroom and became the emission source. The eight occupants included one professor in his 70s and seven students between 20–35 years old, who were all wearing face masks during the experiment. $S$ was then calculated as the product of the total occupant number and particle emission rate per occupant. The particle concentration at the start of the experiment was measured to be 850 # cm$^{-3}$ with only the AHU operating at a flow rate of 0.047 m$^3$ s$^{-1}$. The average outdoor ambient concentration of 6742 # cm$^{-3}$ was recorded, and the wall-loss coefficient was the same as the value calculated in the previous step. By fitting the measurement data with Eq. (8), it was found that each occupant generated particles with an emission rate of 10 # s$^{-1}$, as shown in Fig. 3. This value is in good agreement with the measured data reported by He et al. (2021) on the aerosol generation rate by an individual breathing or speaking. The fitted curve has an $R^2$ value of 0.499, as indicated by the figure. The concentration increase in Fig. 3 was caused by not only the occupants but also...
To recapitulate what has been presented in this section, the empirical wall-loss coefficient was found to be $1.71 \times 10^{-4}$ m s$^{-1}$ and the particle emission rate per occupant, $10$ # s$^{-1}$.

### 4 RESULTS AND DISCUSSION

To compare the particle concentration decay predicted by the analytical model with experimental data, measurements were conducted under four experimental conditions. Two system flow rates of $0.142$ m$^3$ s$^{-1}$ (300 CFM) and $0.047$ m$^3$ s$^{-1}$ (100 CFM) were applied for the AHU. Filters with different efficiency classes were installed in the ventilation systems. MERV 15 filters with an efficiency of 0.9 were equipped in the AHU, while MERV 13 (efficiency of 0.7) or MERV 8 (efficiency of 0.17) were used for the FCU. As the majority of the particles are in the 0.3–1.0 µm size range used to determine a filter’s MERV value, results in that size range were chosen here (ANSI/ASHRAE, 2012). For each experiment, the FCU system was running at its full capacity with a flow rate of $0.354$ m$^3$ s$^{-1}$ (750 CFM). Before all the measurements, an atomizer was applied to generate particles with 1% NaCl solution, while during the measurements, all particle sources were turned off.

The particle number concentrations for each condition shown in “Results” are normalized by the corresponding initial concentration measured during the experiments. Fig. 4 shows the normalized particle number concentration as a function of time for the four experimental conditions with both the measurement data and analytical results plotted. By increasing the AHU flow rate or upgrading the filter’s efficiency class in the FCU, the particle concentration in the classroom achieves higher decay rates. In general, the analytical model follows the decaying trends of the measurement data reasonably well. The discrepancy between the two can be due to the well-mixed assumption of the analytical model, impact of local mixing caused by airflows in the classroom, effect of additional surface area from indoor furniture on particle deposition, and inaccuracy of size-dependent input parameters in the analytical equation such as the filtration efficiencies. At 15 min, the particle concentration is reduced by 86.9%, 79.9%, 65.5%, and 50.0% for the four scenarios, as predicted by the analytical model.

To evaluate the ability of the AHU system itself in controlling the indoor contaminant levels, the analytical model was applied to calculate the normalized particle number concentrations with only the AHU operating. Two system flow rates of $0.047$ m$^3$ s$^{-1}$ (100 CFM) and $0.142$ m$^3$ s$^{-1}$ (300 CFM) were chosen. For each flow rate, the three filter efficiency classes of MERV 8/13/15 were applied. The initial indoor particle concentration and outdoor ambient concentration were
assumed to be 10,000 # cm$^{-3}$ and 4,000 # cm$^{-3}$, respectively. Results calculated by the analytical model are plotted in Fig. 5. The solid curves represent cases with the flow rate of 0.047 m$^3$ s$^{-1}$ (100 CFM), while the dashed curves indicate cases with the higher flow rate of 0.142 m$^3$ s$^{-1}$ (300 CFM). With the MERV 15 filter equipped and a flow rate of 0.142 m$^3$ s$^{-1}$ (300 CFM), the AHU system can reduce the indoor particle number concentration by 56.5% in the first 15 min of operation. This is the normal operating condition of the ventilation system of a typical modern classroom at the University of Minnesota.

Fig. 6 indicates the normalized particle number concentration when only the FCU operates under six different conditions. Two system flow rates of 0.177 m$^3$ s$^{-1}$ (375 CFM) and 0.354 m$^3$ s$^{-1}$ (750 CFM) were considered, as shown by the solid and dashed curves, respectively. The results illustrate that by upgrading the ventilation system with a higher filter efficiency class, the FCU performance can be significantly enhanced. For instance, at a system flow rate of 0.354 m$^3$ s$^{-1}$...
(750 CFM), if the MERV 8 filter is replaced by the MERV 13 filter, particle removal percentage at 15 min will be changed from 38.2% to 75.1%. Currently, the university classrooms are mostly equipped with MERV 8 filters in the FCU systems. It is suggested that these filters should be upgraded to MERV 13 so that the FCU system performance can be improved substantially.

Some old classrooms in the university do not have an AHU or FCU system, in which case IACs are required for particulate contaminant removal. Fig. 7 gives the analytical results for the particle concentration decay while different numbers of IACs are running in the classroom. The flow rate of each air cleaner was assumed to be 0.0755 m³ s⁻¹ (160 CFM), which is the maximum flow rate of the Oreck AirInstinct air purifier (Model AIR108), a common device at the university. An indoor air cleaner is always equipped with a high-efficiency particulate air (HEPA) filter, which has a filtration efficiency close to 1.0. Here we used an efficiency of 0.96 which is based on our experimental evaluation of these air cleaners. As shown in Fig. 7, the particle concentration can be reduced by 41.8%, 59.0%, 79.7%, and 90.0% for the one-cleaner, two-cleaner, four-cleaner, and six-cleaner scenarios, respectively. This result illustrates that even if a classroom does not have its AHU or FCU system, the indoor particle concentration can still be reduced fairly quickly by introducing enough air cleaners.

5 SUMMARY

We have developed an analytical model for estimating the particle number concentration decay in indoor classrooms and residences that factors in the filtration efficiencies of AHUs and FCUs, effects of indoor air cleaners, particle deposition on walls, and particle emission from occupants. Based on experimental measurements, we determined the wall-loss coefficient, $k_w$, and the particle generation rate per occupant to be $1.71 \times 10^{-4} \text{ m s}^{-1}$ and $10 \text{ # s}^{-1}$, respectively, and found good agreement between the modeling predictions and the observation data for four scenarios, validating the derived analytical model. We then employed the model to analyze the change in the indoor particle concentration under different operating conditions.

One limitation of this model is its assumption that the AHU supplies only outdoor air, whereas in the real world, an AHU typically supplies a mixture of outdoor air and recirculated air from other classrooms in the same building—a scenario that should be addressed in the future. In addition, although Eq. (8) can be used for any airborne contaminant, several of its parameters depend on the particle size, including the filtration efficiencies, wall-loss coefficient, and emission source term, which confines the application of the model to a specific range of aerodynamic diameters, regardless of the particles' morphology or chemical composition. Furthermore, the
model estimates the total particle number concentration by integrating the results over a range of particle sizes rather than examining any size in particular. In our study, we selected a size range of 2.5 nm–2 µm, which corresponds to the limits of the instrument used to experimentally measure the wall-loss coefficient and the occupant emission rate. However, as the analytical results change with the outdoor particle size distribution, filter efficiency, and source particle size distribution, the model’s integrated prediction varies according to the particle-size-dependent parameters. This issue can be addressed in a future study on a size-dependent analytical model.

The analytical model has been integrated with a graphical user interface and made freely available as a web application at cfr.umn.edu under the Particle Decay Model tab. The user should input the following parameters: the dimensions of the classroom; flow rates of the AHU, FCU, and IAC; filter classes for the AHU, FCU, and IAC; initial indoor particle number concentration; outdoor ambient particle number concentration; and total number of occupants. Because the efficiency of a filter is a function of the particle size and the face velocity, these values must be correct in order to produce accurate results. The user can also compare the particle concentration decay rates in up to three scenarios by checking “Case 1,” “Case 2,” and, if necessary, “Case 3.” As the conditions from Case 1 are automatically applied to Case 2 and Case 3, only the changed variable(s) must be updated, e.g., substituting “MERV 8” in Case 1 with “MERV 13” in Case 2 to assess the effect of a different filter class. By offering a valuable practical tool for facility engineers to evaluate the indoor particle concentration reduction rates on school campuses, we believe that our work will be highly beneficial to controlling air quality in classrooms.

NOMENCLATURE

| Symbol | Definition                                      |
|--------|-----------------------------------------------|
| $A_s$  | internal surface area of the classroom, m².  |
| $a$    | integration coefficient.                      |
| $k_w$  | wall-loss coefficient, m s⁻¹.                 |
| $M$    | integration coefficient.                      |
| $N$    | particle number concentration, # cm⁻³.        |
| $N_0$  | initial indoor particle number concentration, # cm⁻³. |
| $Q$    | flow rate, m³ s⁻¹.                            |
| $S$    | indoor particle emission rate, # s⁻¹.          |
| $t$    | time, s.                                      |
| $V$    | volume of the classroom, m³.                  |

Greek

| Symbol | Definition                                      |
|--------|-----------------------------------------------|
| $\eta$ | particulate filtration efficiency.            |

Subscripts

| Subscript | Description                                  |
|-----------|----------------------------------------------|
| AHU       | air handling unit                            |
| a         | ambient (outdoor)                            |
| dp        | a specific particle size, µm.                |
| FCU       | fan coil unit                                |
| IAC       | indoor air cleaner                           |

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