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A CFD study on the effect of portable air cleaner placement on airborne infection control in a classroom†

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Abstract

The utilization of portable air cleaners (PACs) is a recommended supplemental approach to help remove airborne pathogens and mitigate disease transmission in learning environments. To improve PAC effectiveness, science-based information is needed to optimize their implementation strategies such as the deployment location, height, and number of PACs. In this study, we developed a Computational Fluid Dynamics (CFD) model to assess how PACs perform in occupied classrooms equipped with displacement and mixing ventilation systems. The results show that PACs with a flow rate of 2.6 h^{-1} reduce the mean aerosol intake of all students by up to 66%. A key benefit of using PACs is to facilitate air mixing and movement in indoor environments with inadequate ventilation, thereby effectively reducing high aerosol concentrations near the infector. Furthermore, our results highlight the impact of PAC location on its performance. PACs achieve the best effectiveness when placed closed to the infector (within a distance <3 m). In the absence of knowing who is infected, deploying a PAC at the center of the room is recommended. Moreover, adjusting PAC flow discharge height to the breathing height of occupants (*e.g.,* 0.9–1.2 m for seated people) can enhance their effectiveness in spaces with poor air mixing.

1. Introduction

Transmission of respiratory infectious diseases (*e.g.*, influenza, measles, tuberculosis, and coronavirus diseases) in schools poses a significant threat to public health and student learning efficiency.[1-5] Classrooms can present a special challenge in preventing the spread of airborne infections due to their relatively high occupant density, long exposure time, and frequent interactions among students and teachers.[5-7] While ventilation plays a crucial role in reducing infection risks, many schools worldwide lack sufficient mechanical or natural ventilation to effectively control infections.[8-11] For instance, the US Government Accountability Office[12] reported that 41% of school districts in the US, representing

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approximately 36 000 schools nationwide, require updates or replacements of their heating, ventilation, and air conditioning (HVAC) systems to improve indoor air quality. Therefore, the utilization of in-room filtration and purification devices is recommended as a supplementary measure to reduce disease transmission in classrooms, according to the US Centers for Disease Control and Prevention (CDC),[13] the Lancet COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel,[14] and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).[15,16]

Portable air cleaners (PACs) have the potential to reduce the airborne transmission of respiratory diseases in classrooms by removing aerosols containing pathogens from the air.[5,6,17-25] Curtius *et al.*[17] assessed the efficacy of a PAC equipped with a High Efficiency Particulate Air (HEPA) filter in a high school classroom. They reported that a PAC with an air change rate of 5.7 h^{-1} could reduce inhaled aerosol dose by a factor of six. Derk *et al.*[18] tested the performance of homemade PACs with an air change rate of 12.4 h^{-1} in a mock classroom and reported up to 73% reductions in aerosol exposure. Rodríguez *et al.*[19] compared the detection of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in indoor air and surface samples before and after the use of a PAC with a flow rate of 290 L s^{-1}. They found that all the air samples and 75% of surface samples were positive before using PAC. After the PAC deployment, all samples except one were negative. Moreover, several modeling studies also highlighted that PACs are effective in mitigating aerosol exposure in classroom environments.[23-25]

In addition to the inherent characteristics of PACs (*e.g.*, flow rate and filter efficiency), the implementation strategies, such as the deployment location, height, and number of PACs can affect their performance in mitigating airborne infection risks.[25-30] Nevertheless, limited studies have investigated the optimal placement of PACs to prevent airborne infections, especially in classroom environments. He *et al.*[25] estimated the distribution of exhaled aerosols in a classroom with various PAC implementation strategies. They found that placing PACs near the infector (within 2.5 m) or close to the horizontal unit ventilator yielded better performance. Moreover, operating a PAC at elevated height (from 0.3 m to 1.3 m above the floor) was also shown to enhance its performance. Na *et al.*[29] measured the aerosol removal efficiency of a PAC placed at different locations in a school classroom. They reported that the PAC was more effective when placed next to the infector. They also observed that inappropriate PAC placement may lead to aerosol dispersion and increase infection risks. While these studies provided valuable insights for optimizing PAC implementation, their models or experiments mainly considered aerosol distributions in unoccupied classrooms. However, the presence of occupants and their thermal plumes (generated by temperature gradients between human body and room air) can have significant impacts on airflow and pollutant transport in near-human microenvironments, thereby affecting aerosol exposure risk of occupants.[31,32] Furthermore, the influences of room ventilation systems (*e.g.*, displacement ventilation *vs.* mixing ventilation) and associated indoor airflow patterns on PAC performance are not well understood.

Given this background, the objective of this study is to evaluate impacts of key characteristics of PAC deployment, including location, height, and number of PACs on aerosol removal effectiveness in occupied classrooms with representative ventilation strategies and airflow patterns. The results can provide science-based guidelines for optimizing the implementation of PACs to reduce airborne infection risks in classrooms.

2. Method

We analyzed how airborne aerosol exposure in an occupied classroom varies with the placement location, height, and number of portable air cleaners (PACs), based on a Computational Fluid Dynamics (CFD) modeling framework as described below.

2.1. Classroom layout and boundary conditions

Fig. 1 displays the layout of the modeled classroom. The room dimensions were set to 8 m (length) × 8 m (width) × 3.5 m (height). Nine seated students and one standing teacher were simulated based on detailed human geometries.[33] Although the use of detailed body geometries increases computational load compared to using simplified geometries such as cuboids or cylinders, it enables more accurate predictions of airflow and aerosol distributions for the near-human microenvironments,[34] which directly impact the estimation of human inhalation exposure. The physical distances between students and the teacher are shown in Fig. 1. The heat load generated by each occupant (75 W) was divided into convective (45%) and radiative (55%) parts.[33,35] The convective heat was applied to the surfaces of human bodies as the Neumann thermal boundary condition, while the radiative part was evenly distributed to the surrounding wall surfaces.[36] Additionally, a 400 W heat production was assigned to the window surface using the Neumann boundary condition to simulate solar heat gain, as suggested by a previous study.[37] Note that we did not include radiation models such as Surface-to-Surface (S2S) or Discrete Ordinates (DO) radiation model in order to reduce computational cost. The use of radiation models should be able to provide more realistic simulation of radiative heat transfer process and should be explored in future work.

We simulated the emission of aerosols from the teacher's mouth during talking, as talking generates a large number of aerosols during classes.[25] Based on the literature, the velocity of exhaled air and aerosols during talking was set at 4 m s^{-1} in a direction 30° downward from horizontal plane.[38-40] The area of mouth was set as 1.15 cm^2,[40] the temperature of exhaled air was 34 °C,[40] and the aerosol volume concentration in the exhaled air was 1×10^{-12}.[41] We employed an inert tracer gas, sulfur hexa-fluoride (SF_6), to simulate the transport of exhaled aerosols. Numerous studies have shown the potential of using tracer gases as proxies for predicting airborne infection *via* small aerosols (<3.5 μm) in indoor environments.[32,40,42-46] In this study, we adopted a tracer gas modeling approach that was tested and verified by Pei *et al.*,[32] which found that the tracer gas model can predict human exposure to small respiratory aerosols with deviations lower than 5%. The tracer gas model incorporates a three-dimensional convection-diffusion mass transfer equation:[47]

$$\frac{\partial(\rho C)}{\partial t} + \nabla \cdot (\rho C u) = \nabla \cdot (D_{\mathrm{eff}} \nabla C) + S_{\mathrm{c}} \tag{1}$$

where ρ is the density of the fluid, C is the tracer gas concentration, t is the time, u is the fluid velocity vector, D_{eff} is the effective diffusion coefficient (including molecular diffusion and turbulent diffusion), and S_c is the source or sink term. To model flow turbulence, we adopted the Reynolds Averaged Navier–Stokes (RANS) approach with the Realizable $k-\varepsilon$ turbulence model due to its good performance in estimating airflows and pollutant dispersions in occupied indoor spaces.[48,49]

To investigate the impact of ventilation systems and associated indoor airflow patterns on PAC performance, we simulated two commonly used ventilation strategies for classrooms: (1) displacement ventilation and (2) mixing ventilation.[50] Displacement ventilation provides low-velocity supply air at the floor level, which creates a buoyancy-driven, stratified airflow pattern in the room that can potentially transport exhaled aerosols from the occupant breathing zone to the upper region of the room.[36] As illustrated in Fig. 2a, we set two in-wall displacement diffusers with a supply air velocity of 0.1 m s^{-1} in the direction perpendicular to the diffuser face. By contrast, mixing ventilation introduces high-velocity supply air at the ceiling level to facilitate room airflow mixing.[36] In this study, we implemented two four-way ceiling diffusers with a supply air velocity of 2.4 m s^{-1} angled at 25° from the ceiling plane. Each diffuser was divided into four regions and the x, y, z components of supply air velocity were specified at each region (see Fig. S1 in ESI†). Fig. 2b illustrates how mixing ventilation enhances the mixing of airborne aerosols in the room compared to displacement ventilation. A more detailed discussion on the effect of ventilation strategy on aerosol transport will be provided in Section 3.1. For both ventilation strategies, the supply air flow rate was set to 320 m^3 h^{-1} with 100% outdoor air, equivalent to an air change rate of 1.4 h^{-1}, based on the minimum ventilation requirement defined by ANSI/ASHRAE.[51] We modeled the ASHRAE minimum ventilation since it represents the case where the ventilation rate is low and the use of PACs is highly necessary. Future studies are warranted to explore the impact of supply air flow rate on the performance of PACs. The supply air temperature was set to 17 °C to simulate cooling condition.[52] Note that different supply air temperatures (*e.g.*, cooling *vs.* heating) can lead to different airflow patterns in the room, thereby affecting pollutant transport. For instance, previous experimental and numerical studies showed that warm air supplied at ceiling level can cause poor mixing in the lower part of the occupied space due to temperature stratification.[53,54] Future work is needed to examine the potential influence of supply air temperature on PAC performance. The room air exhaust was placed at the ceiling with a pressure outlet boundary condition.[36]

2.2. Portable air cleaner model and parametric analysis

We modeled a high efficiency cuboid PAC with dimensions of 0.4 m (length) × 0.2 m (width) × 0.4 m (height), as depicted in Fig. S2.† The PAC had an air intake located at the lower portion of the front side, and filtered air was discharged from the top of the PAC. At the air intake, a uniform surface mass-flux was applied. At the PAC discharge, 100% clean air was emitted straight upwards with the same mass-flux rate and temperature as the flow at the PAC intake using user-defined function.[30] The clear air delivery rate (CADR) of the PAC was set as 575 m^3 h^{-1} (338 cfm), targeting a total non-infectious air delivery rate (CADR

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+ ventilation rate) of 895 $m^3\ h^{-1}$ (air change rate = 4 h^{-1}), which is recommended by The Lancet COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel.[14] These PAC specifications were chosen to reflect realistic configurations based on a brief survey of commercially available PACs.

To examine the optimal implementation strategy of PACs in the classroom, we evaluated three key parameters: PAC location, PAC number, and PAC air discharge height. For each ventilation strategy (displacement and mixing ventilation), we assessed the performance of a single PAC placed at three different locations: the back, center, and front of the room, with a distance to the teacher (infector) as 8 m, 3 m, and 0.5 m, respectively. Moreover, we simulated another set of scenarios with the use of three PACs, each with a lower CADR (190 $m^3\ h^{-1}$), located at the back, center, and front of the room, maintaining the same total CADR as the case with a single PAC. For the case with a single PAC at the back of the room and the case with three PACs, two PAC air discharge heights were investigated: 0.4 m (representing PACs placed on the floor) and 0.9 m (representing PACs placed on chairs or desks). Including the baseline cases without the use of PACs, a total of 14 simulation cases were tested, as summarized in Table 1.

In each simulation case, we monitored the transient aerosol inhalation of each student over 60 minutes (*i.e.,* the length of a class period) at a 1 second time step, by calculating aerosol concentration within the human breathing zone (a 0.006 m^3 cuboid volume below the nose tip).[30] Furthermore, we employed a widely used exposure risk assessment parameter, intake fraction (iF),[40,55,56] which is the ratio of inhaled pollutant mass by the exposed occupant (M_{inhale}) to the exhaled pollutant mass from the infector (M_{exhale}):

$$\mathrm{iF} = \frac{M_{\mathrm{inhale}}}{M_{\mathrm{exhale}}} = \frac{\int_0^T Q_{\mathrm{b}} C_{\mathrm{bz}}(t)\mathrm{d}t}{\int_0^T E(t)\mathrm{d}t} \tag{2}$$

where $Q_{\mathrm{b}} = 0.6\ \mathrm{m}^3\,\mathrm{h}^{-1}$ is the breathing flow rate for an individual at rest,[38] $C_{\mathrm{bz}}(t)$ is the aerosol concentration in the breathing zone of the exposed occupant, $E(t)$ is the aerosol emission rate, and T is the duration of aerosol emission (60 minutes in this study).

2.3. Mesh generation and model quality control

To generate the computational grid, we used a polyhedral mesh due to its flexibility in capturing detailed human geometries and its potential to reduce computational cost while maintaining reasonable accuracy.[34,57,58] As shown in Fig. S3,† we refined the meshes in the vicinity of human bodies and in the human breathing zone to enhance the modeling accuracy of aerosol transport near occupants. The first cell size adjacent to human surfaces was set to 5 mm with a cell stretch rate of 1.35, resulting in average $y+$ values (dimensionless wall distance) at human surfaces below 4.[34] The target cell size in the human breathing zone was set as 0.05 m. Moreover, we refined the meshes in other grid-sensitive regions, including the proximity of supply air diffusers, exhausts, windows, PAC inlets, and PAC outlets, with the target cell size as 0.08 m (minimum cell size as 0.04 m), 0.08 m (0.04 m), 0.2 m (0.05 m), 0.04 m (0.02 m), and 0.04 m (0.02 m), respectively. Approximately 200 000 cells were generated for the computational domain. We conducted a grid sensitivity analysis to determine if the adopted mesh strategy was capable of producing reliable estimates of breathing zone aerosol concentrations. We tested three mesh generation strategies for the case with a single PAC placed at the back of the room (Grid 1, Grid 2, and Grid 3 with 148 000, 200 000, and 280 000 cells, respectively). Table S1† summarizes detailed mesh parameters of these mesh strategies. As illustrated in Fig. S4,† the differences in predicted breathing zone concentrations between simulations with Grid 2 and Grid 3 were within the simulation uncertainties (standard deviations), suggesting that Grid 2 was able to provide converged estimates of breathing zone aerosol concentrations.

Furthermore, we carried out an experimental validation to assess the prediction capabilities of the modeling strategies used in this study (*e.g.,* turbulence model, tracer gas model, mesh construction, and heat transfer model). A full description of the validation process is provided in ESI Text S1 in the ESI.† In general, the comparisons of our CFD simulation results of air speeds and tracer gas concentrations against the measurements in a full-scale environmental chamber suggested that our modeling strategies were able to provide general insights into the airflow and tracer gas transport in occupied, ventilated indoor spaces. We also assessed the accuracies of the CFD simulations by comparing the results against the well-mixed mass balance model:[44,59]

$$C_{\text{in}} = \frac{E}{(\lambda + \beta)V}\left(1 - \mathrm{e}^{-(\lambda + \beta)t}\right) \tag{3}$$

where C_{in} is the exhaust aerosol concentration, E is the aerosol emission rate, λ is the ventilation rate, β is the PAC filtration rate, V is the room volume, and t is the time. The comparison results are provided in the Section 3.

3. Results and discussion

3.1. Effect of ventilation strategy

Fig. 3 depicts the temporal evolution of aerosol distribution in the classroom under displacement ventilation (DV) and mixing ventilation (MV), without the use of portable air cleaners (PACs). The figure shows notable differences in the aerosol transport patterns between DV and MV. In the case of DV, the high-concentration exhalation jet from teacher's (infector) talking travels a longer distance compared to MV. Under DV, the high-concentration breath can quickly reach the student in the first row (at a distance of 1.2 m from the infector) within 1 min, and reach the student in the second row (at a distance of 3.2 m from the infector) within 10 min. However, under MV, the high-concentration exhalation jet has a shorter travel distance and becomes diluted before reaching the student in the first row.

This difference is attributed to the different airflow patterns generated by DV and MV. DV introduces low-momentum, cool air at the floor level, creating buoyancy-driven thermal plumes near occupants due to the temperature gradients between human bodies and the room air (see the airflow and temperature distributions in Fig. S5 and S6†). These thermal plumes have relatively high vertical airspeeds and can potentially draw air pollutants from the human breathing zone towards the upper region of the room, resulting in stratification of pollutant distribution.[31,36] However, in this case, the thermal plumes are not strong enough to disrupt the exhalation jet, and exhaled aerosols can accumulate within the students' breathing zone. This is mainly due to the high momentum of the exhalation jet from talking as well as the relatively low ventilation rate employed in this case (air change rate = 1.4 h^{-1}). Note that such phenomenon may also be observed in classrooms with natural ventilation at minimum ventilation rates (which exhibit buoyancy-driven airflow patterns) such as portable classrooms.[60]

In contrast, MV introduces high-velocity supply air at the ceiling level, enhancing room airflow mixing (see Fig. S5 and S6†). Therefore, room airflow under MV exhibits higher air speeds and stronger mixing compared to DV, which can effectively disrupt the exhalation jet and prevent high-concentration breath from reaching susceptible students' breathing zone. However, Fig. 3 indicates that even with MV, the aerosol concentration does not become completely uniform within 60 min, suggesting that the relatively low ventilation rate applied in this study cannot achieve well-mixed air condition within 60 min.

Fig. 4 presents the time-varying inhaled aerosol concentrations of nine students under DV and MV, compared to the well-mixed mass balance model. In the case of DV (Fig. 4a), there is a rapid increase in the inhaled concentration of Student 2 within 1 min (see the student placement in Fig. 4). At 10 min, the aerosol intake fraction of Student 2 under DV (0.0036) is six times higher than that under MV (0.0005). Moreover, the inhaled concentration of Student 5 is also notably higher under DV than MV, with an 82% higher intake fraction at 10 min. Student 2 and Student 5 are positioned at 1.2 m and 3.2 m distances from the infector, respectively, in a face-to-face orientation with the infector. The elevated exposures of these students under DV are attributed to the long exhalation jet observed in Fig. 3. For students sitting at greater distances from the infector (*e.g.*, Student 8) or not directly facing the infector (*e.g.*, Student 3), the inhaled concentrations are moderately lower under DV compared to MV, as MV promotes the mixing of high-concentration breath with room air. Overall, the average 60 min intake fraction ($\times 10^{-4}$) of nine students under DV is 12.02 (standard deviation, SD = 13.12), which is 40% higher than that under MV (8.64 with SD = 3.34). These results indicate that without the use of PAC, DV with low ventilation rates can potentially lead to elevated airborne exposure for students within a close distance (<3 m) from the infector, especially for those who directly face the infector. In contrast, MV can perform well in mitigating the short-range (defined as distance <1.5 m) exposure risk. Similar observations regarding the performance of DV and MV in reducing aerosol exposure in indoor spaces have been reported in previous studies conducted in a two-person office[32] and a two-bed hospital ward.[43] Our results reveal that these observations also apply to relatively large indoor spaces with higher occupant densities such as classrooms.

Regarding the comparison of simulation results with the well-mixed mass balance model, Fig. 4a shows that the well-mixed model significantly underestimates the inhaled concentrations of students in close proximity to the infector (*e.g.*, Student 2) under DV. However, under MV, the well-mixed model can provide more reasonable predictions of student inhaled concentrations (Fig. 4b). The average 60 min intake fraction ($\times 10^{-4}$)

predicted by the well-mixed model is 9.03, which is 25% lower than that under DV and is 4.5% higher than that under MV.

3.2. Effect of portable air cleaner location

This section elaborates on the effect of the placement location of the PAC on its performance in removing exhaled aerosols. Fig. 5 provides the temporal development of aerosol distribution in the classroom under DV with four PAC deployment scenarios: without the use of PAC, and with a single PAC placed at distances of 8 m, 3 m, and 0.5 m from the infector, respectively (*i.e.*, at the back, center, and front of the room). The results illustrate that compared to the case without PAC, the utilization of PAC can generally reduce aerosol concentrations in the classroom and dilute the high-concentration exhalation jet emitted by the infector. However, the effectiveness of the PAC strongly depends on its location and its distance from the infector. When the PAC is placed at the back of the room (8 m distance from the infector), while it can help to reduce aerosol concentrations in the room, there are still relatively high concentration plumes within the occupant zone. Placing the PAC at the center of the room (3 m distance from the infector) or at the front of the room (0.5 m distance from the infector) can effectively dilute the high-concentration exhalation jet and lower aerosol concentrations in the occupant zone. This is because when PAC is placed near the infector, it can remove the respiratory aerosols before they spread throughout the room. Furthermore, the high-momentum discharged airflow from the PAC (face velocity = 2 m s^{-1} in this case) placed near the infector can increase the speed and mixing of the airflow around the infector, thereby more effectively diluting the high-concentration exhaled flows and preventing elevated exposures in the proximity of the infector. This phenomenon is also illustrated by the air speed contours provided in Fig. S7.†

Fig. 6 shows the time-varying inhaled aerosol concentrations of nine students under DV with various PAC placement locations. For all three PAC locations tested in this study (8 m, 3 m, and 0.5 m distance from the infector), the PAC can yield notable reductions in student inhaled concentrations, particularly for students in close proximity to the infector (*e.g.*, Student 2 and Student 5). For Student 2, the 10 min aerosol intake fraction is reduced by 70.3%, 94.5%, and 94.8% when the PAC is placed at distances of 8 m, 3 m, and 0.5 m from the infector, respectively; For Student 5, the reductions are 29.9%, 92.4%, and 92.0%, respectively. The average 60 min intake fraction ($\times 10^{-4}$) of the nine students is 6.56 (SD = 3.79), 4.52 (SD = 1.84), and 4.87 (SD = 0.67) for the cases with the PAC placed at 8 m, 3 m, and 0.5 distance from the infector, which is 45.4%, 62.4%, and 59.5% lower than the case without the use of PAC (12.02 with SD = 13.12). Clearly, placing the PAC at a close distance (*e.g.*, <3 m) to the infector achieves the best performance, especially in reducing short-range airborne transmission risk.

Furthermore, Fig. 6 shows that when the PAC is placed at distances of 3 m or 0.5 m from the infector (Fig. 6c and d), the inhaled aerosol concentrations of the nine students are aligned with each other and with the well-mixed mass balance model. This reveals that a key benefit of using PAC is to enhance air mixing and movement in classrooms with low ventilation rates, thereby reducing the risk of aerosol accumulation in the occupant zone. A previous experimental study also reported that the use of PACs can break up airflow stratification and improve mixing in the room.[53] This also implies that the well-mixed mass balance model can potentially work well in predicting airborne aerosol exposure in a room with the PAC placed near the infector. Considering that the PAC achieves its best performance when placed near the infector, this finding suggests that the well-mixed assumption may serve as a good approximation for estimating airborne exposure when the PAC is placed at its optimal location.

Similar analyses to Fig. 5 and 6 were also conducted for simulations with MV, as shown in Fig. S8 and S9.† The average 60 min intake fraction of the nine students under MV are summarized in Table 1. In general, the use of PAC is also effective under MV, reducing the average student intake fraction by up to 66% (see Table 1). Moreover, placing the PAC at distances of 3 m or 0.5 m from the infector results in 50% or 31% lower aerosol exposure compared to placing the PAC at a distance of 8 m from the infector. These results support the recommendation of placing the PAC close to the infector (<3 m distance) for both DV and MV systems.

Only a few studies have examined the effects of PAC deployment location on its performance in mitigating airborne disease transmission in classrooms. He *et al.*[25] numerically modeled an unoccupied classroom (only the infector is simulated) equipped with a horizontal unit ventilator (air change rate = 2 h^{-1} and filtration efficiency = 50%). They found that a PAC (flow rate = 2.7 h^{-1}) placed at 2.5 m distance from the infector can remove 207% more respiratory aerosols than the PAC placed at 9 m distance from the infector. Na *et al.*[29] conducted experiments in an unoccupied classroom without a mechanical ventilation system. They reported that when placing a PAC (flow rate = 0.74 or 3.4 h^{-1}) next to a particle generator (which simulates aerosol emission due to sneezing), the PAC has improved particle removal efficiency compared to placing it at 8 m distance from the generator. Our results suggest that in occupied classrooms with DV or MV systems, the PAC placed within 3 m distance from the infector achieves the best performance, which agrees with previous studies. Note that one limitation of this study is that only one location of the infector was simulated. Considering that PAC has better performance when placed closer to the infector, the optimal location of PAC may vary depending on the location of the infector. In practical situations where the location of the infector is not identified beforehand, the PAC placed at the center of the classroom may be most effective, as it is most likely to be within the proximity of potential infectors and benefit the most occupants in the room. In contrast, the PAC placed at the room edges are more likely to be far from the infectors if they are on the other side of the room (*e.g.*, the PAC is at the back of the room while the infector is at the front). In such a case, the PAC can still work in reducing aerosol exposure risk, but can be relatively less effective. Dai & Zhao[27] assessed PAC performance in an office room while varying infector locations and found that locating PAC at the center of the room is the most effective. Note that this study focuses mainly on the effect of PAC location on its performance in removing respiratory aerosols, whereas other factors that may affect its optimal location (such as noise level and access to power outlet) are not considered.[18] For example, a PAC with a flow rate >300 cfm can have a sound level >60 dB, which should be taken into account when deploying the PAC.

3.3. Effect of portable air cleaner number and height

In addition to PAC placement location, we also investigated the influence of PAC discharge height and PAC number on aerosol removal efficiency. Fig. 7 provides a summary of the average aerosol intake fraction of the nine students (at 60 min) for all simulation cases, including seven PAC implementation strategies: without PAC (labeled as No PAC at the *x*-axis), and with a single PAC placed at the back (PAC Back), at the center (PAC Center), and at the front (PAC Front) of the room with a discharge height of 0.4 m; a single PAC at the back of the room with a discharge height of 0.9 m (PAC Back High); three PACs at the back, center, and front of the room, with a discharge height of 0.4 m (Three PACs); and three PACs at the back, center, and front of the room, with a discharge height of 0.9 m (Three PACs High). Note that the total flow rate of three PACs is equal to the case with a single PAC. The red dots represent the intake fractions of different students.

Under DV (Fig. 7a), the ranges of intake fractions of students are larger than those under MV (Fig. 7b) due to the heterogenous aerosol distribution under DV. Moreover, under DV, in the case without the use of PAC (No PAC), there is an outlier with a high intake fraction, representing elevated short-range exposure caused by the infector's exhalation jet (as observed in Fig. 3). The utilization of a single PAC (PAC Back, PAC Center, PAC Front) can effectively prevent such elevated exposure risk, particularly when placing the PAC at the center or front of the room (within 3 m distance to the infector). Furthermore, Fig. 7a shows that in the case with a single PAC placed at the back of the room, adjusting the PAC discharge height from 0.4 m (PAC Back) to 0.9 m above the floor (PAC Back High) can enhance the PAC performance in mitigating aerosol exposure. The average intake fraction ($\times 10^{-4}$) of the nine students is 5.27 (SD = 1.82) when the discharge height is 0.9 m, which is 20% lower than that with a discharge height of 0.4 m (6.56 with SD = 3.79). This is because when elevating the PAC discharge height to 0.9 m above the floor, which is roughly the breathing height of seated people, the PAC discharged airflow can more effectively enhance air movement and dilute contaminated air within the breathing zone. The potential benefit of increasing the height of PAC is also suggested by previous studies.[25,61]

Regarding the influence of PAC number, Fig. 7a shows that in the simulated classroom under DV, the deployment of three PACs with a discharge height of 0.4 m (Three PACs) is not effective in mitigating short-range exposure, which results in an even higher short-range intake fraction (the outlier) than the case without PAC. This is likely because the three PACs individually have flow rates and discharge velocities one-third of those in the case with a single PAC. In the modeled classroom with poor mixing (displacement ventilation with minimum ventilation rate), these relatively low-momentum PAC airflows are not as effective as a single PAC with a high flow rate in facilitating airflow mixing near the infector, leading to high aerosol concentrations near the infector.[62,63] Note that our model simulates a classroom with poor air mixing and the distance between the infector and the nearest receptor is relatively small (1.2 m). The result may differ in cases with higher ventilation rates or larger distances between the infector and the receptor.[26] Moreover, Fig. 7a indicates that increasing the discharge height of three PACs (Three PACs High) from 0.4 m to 0.9 m results in a 50% reduction in average student intake fraction ($\times 10^{-4}$), from 9.62 (SD =

15.30) to 4.77 (SD = 7.08). Furthermore, with the elevated height, three PACs can lead to a 27% lower average intake fraction than a single PAC at the back of the room.

Previous studies have presented contradictory conclusions regarding the performance of multiple PACs compared to a single PAC for the same total flow rate. For instance, He *et al.*[25] reported that compared to using a single PAC, deploying two PACs with lower flow rates can capture more respiratory aerosols in a classroom, although two PACs lead to localized high concentration regions near the infector. However, Castellini Jr *et al.*[30] found no significant benefit in utilizing two PACs compared to a single PAC in a conference room. These conflicting results are likely attributed to different room airflow patterns and their interactions with PAC flows in these studies. He *et al.*[25] considered a mixing airflow pattern produced by a horizontal unit ventilator (air change rate = 2 h^{-1}), while Castellini Jr *et al.*[30] examined a buoyancy-driven stratified airflow generated by an overhead heating system (air change rate = 4.2 h^{-1}). In general, the effectiveness of deploying multiple PACs with lower flow rates could vary depending on ventilation conditions, indoor airflow patterns, and occupant locations in the room. Note that a key advantage of using multiple PACs is that they have smaller sound levels compared to a single PAC with high flow rate. Therefore, with appropriate implementation strategies considering room airflows and occupant locations, the use of multiple PACs has the potential to outperform a single PAC. Nevertheless, more systematic studies are needed to further investigate this issue.

Note that the effects of PAC number and discharge height are less significant under MV (Fig. 7b) compared to DV cases. This is because room air is more mixed under MV than under DV; therefore, changes in PAC flows have less impact on the general patterns of indoor airflow and aerosol distributions.

Several limitations of this study should be noted. Firstly, while this study provides general trends of how PACs perform in a classroom, the simulated classroom in this study has a specific size, layout, and occupant placement due to available computational resources. The effects of different classroom configurations should be further investigated.[25] Secondly, this study does not consider the influence of movements and postures of occupants, which may affect airflow and pollutant transport in the room. Thirdly, although we investigated the effect of ventilation strategies (displacement ventilation *vs.* mixing ventilation) on the performance of PACs, we did not explore the potential impacts of configurations and locations of supply diffusers and the exhaust. Fourthly, this study focuses on the effectiveness of PACs in reducing respiratory disease transmission through small airborne aerosols. Future research should explore the application of PACs in mitigating other transmission routes, such as direct contact transmission *via* large droplets and fomite transmission.[22,64,65]

4. Conclusions

This study aims to provide research-based information for optimizing implementation strategies of portable air cleaners (PACs) to reduce airborne infection risk in classrooms. Based on the study results, we found that:

1. The use of PACs is effective in reducing airborne infection risk in classrooms. In our case studies, PACs with a total flow rate of 2.6 h^{-1} can reduce the mean aerosol intake of all students in the classroom by up to 66%. Particularly, the utilization of PACs facilitates air mixing and movement in the room, thereby reducing elevated aerosol concentrations near the infector and mitigating near-field airborne infection risk. This is especially advantageous in rooms with poor air mixing, such as classrooms with displacement ventilation at low ventilation rates (*e.g.*, ASHRAE minimum requirement). Furthermore, given the enhanced air mixing due to PACs, the well-mixed mass balance model can potentially provide quick and reasonable predictions of airborne aerosol exposure in a room equipped with PACs.
2. The deployment location of PACs is a critical factor affecting their effectiveness in removing exhaled aerosols. In general, PACs achieve the best performance when placed near the infector (*e.g.*, <3 m distance). In the absence of knowingwho is infected, placing PAC at the center of the classroom is recommended, as it is more likely to benefit the most occupants in the room.
3. Adjusting the PAC discharge height to the occupant breathing height (*e.g.*, 0.9–1.2 m for seated people) can improve their effectiveness in mitigating aerosol exposure in classrooms with poor air mixing.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data availability

Data for this article, including data shown in Fig. 4, 6, and S9,† are available at Harvard Dataverse at https://doi.org/10.7910/DVN/J6BSA2.

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Environmental significance

Airborne transmission of infectious diseases (*e.g.*, COVID-19, influenza, measles) in indoor environments poses a significant threat to public health. The use of portable air cleaners (PACs) has been recommended by CDC and WHO to help remove airborne aerosols and create healthy indoor environments. In addition to the inherent characteristics of PACs, the implementation strategies, such as deployment location, can have a considerable impact on their effectiveness. However, little information is available for optimizing the implementation of PACs in school environments with consideration of indoor airflow patterns and aerosol transport dynamics. This study provides new insights into the transport patterns of airborne aerosols in ventilated indoor spaces and optimal implementations of PACs in learning environments.

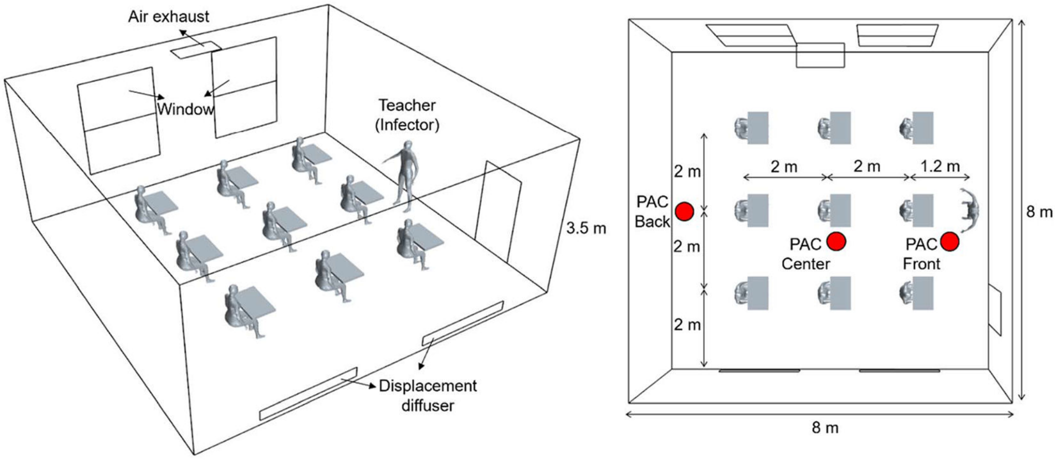

Fig. 1.
Three-dimensional view (left) and top view (right) of modeled classroom. PAC: portable air cleaner.

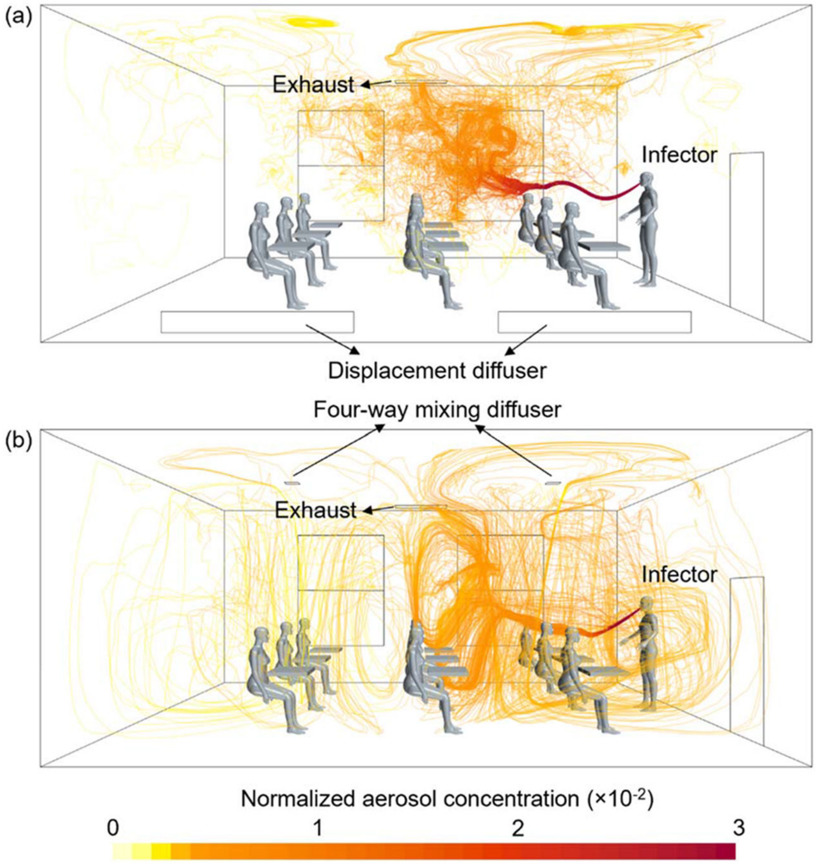

Fig. 2.

Streamlines of exhaled aerosols in the classroom with (a) displacement ventilation and (b) mixing ventilation. The concentrations are normalized by emission concentration.

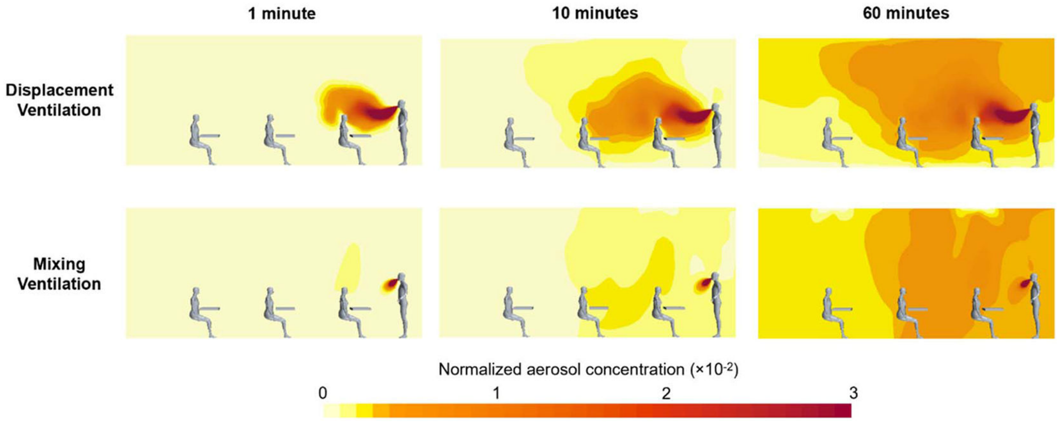

Fig. 3.

Temporal development of aerosol concentration distribution under displacement ventilation and mixing ventilation. No portable air cleaner is applied. The concentrations are normalized by emission concentration.

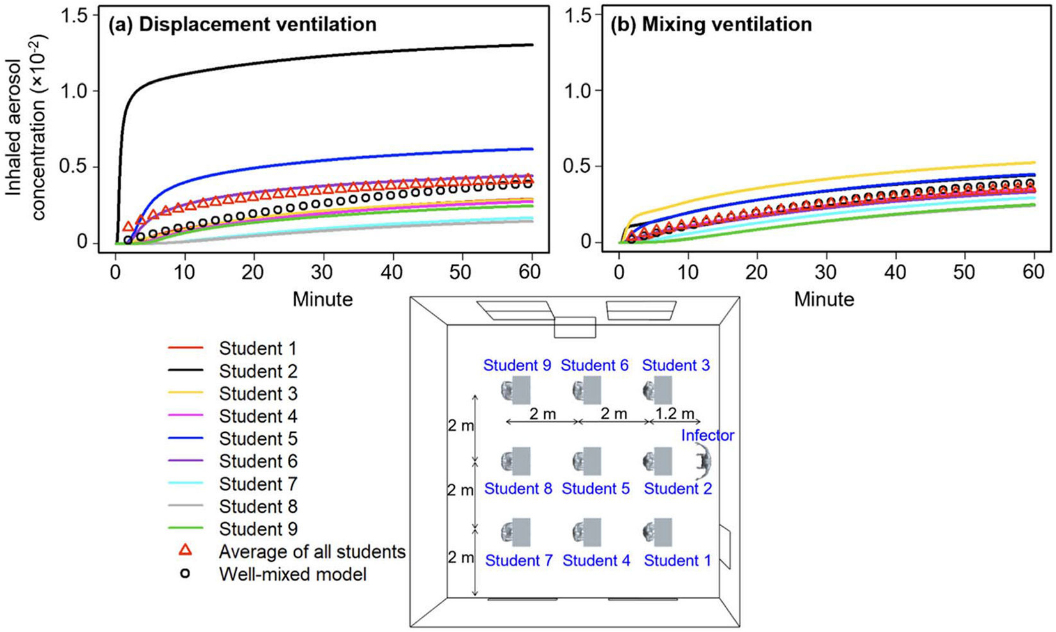

Fig. 4.

Transient inhaled aerosol concentration of nine students under (a) displacement ventilation and (b) mixing ventilation. The simulation results are compared with the well-mixed mass balance model. No portable air cleaner is applied. The concentrations are normalized by emission concentration.

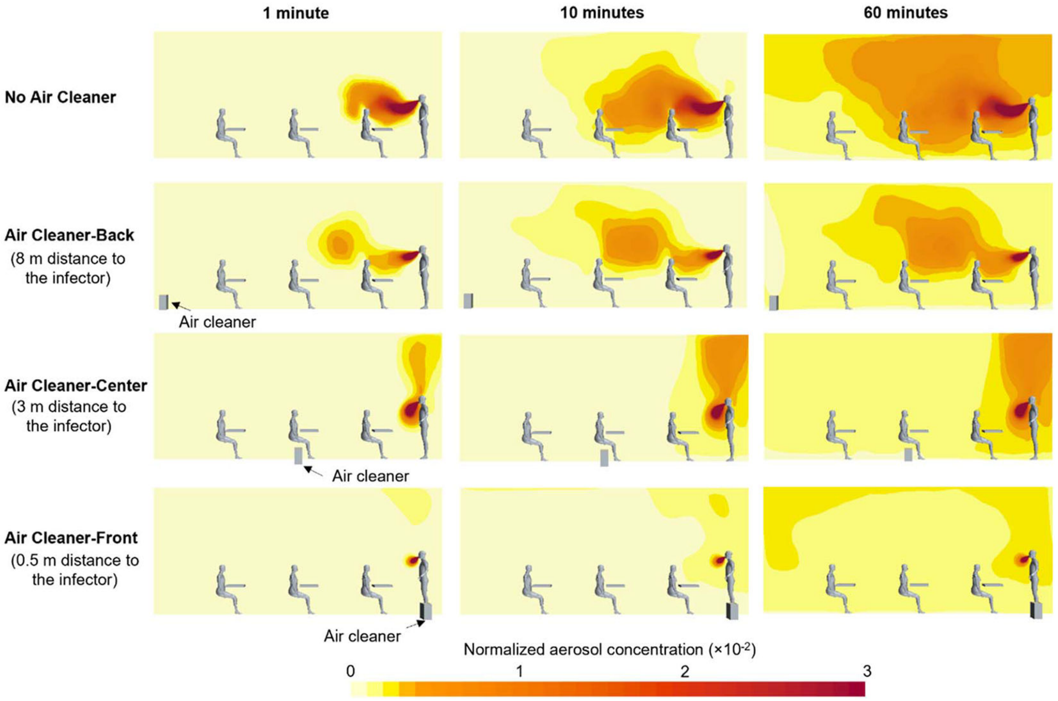

Fig. 5.

Temporal development of aerosol concentration distribution under displacement ventilation. Four scenarios of deployment of portable air cleaner are shown: without air cleaner and with a single air cleaner at 8 m, 3 m, and 0.5 m distance to the infector. The concentrations are normalized by emission concentration.

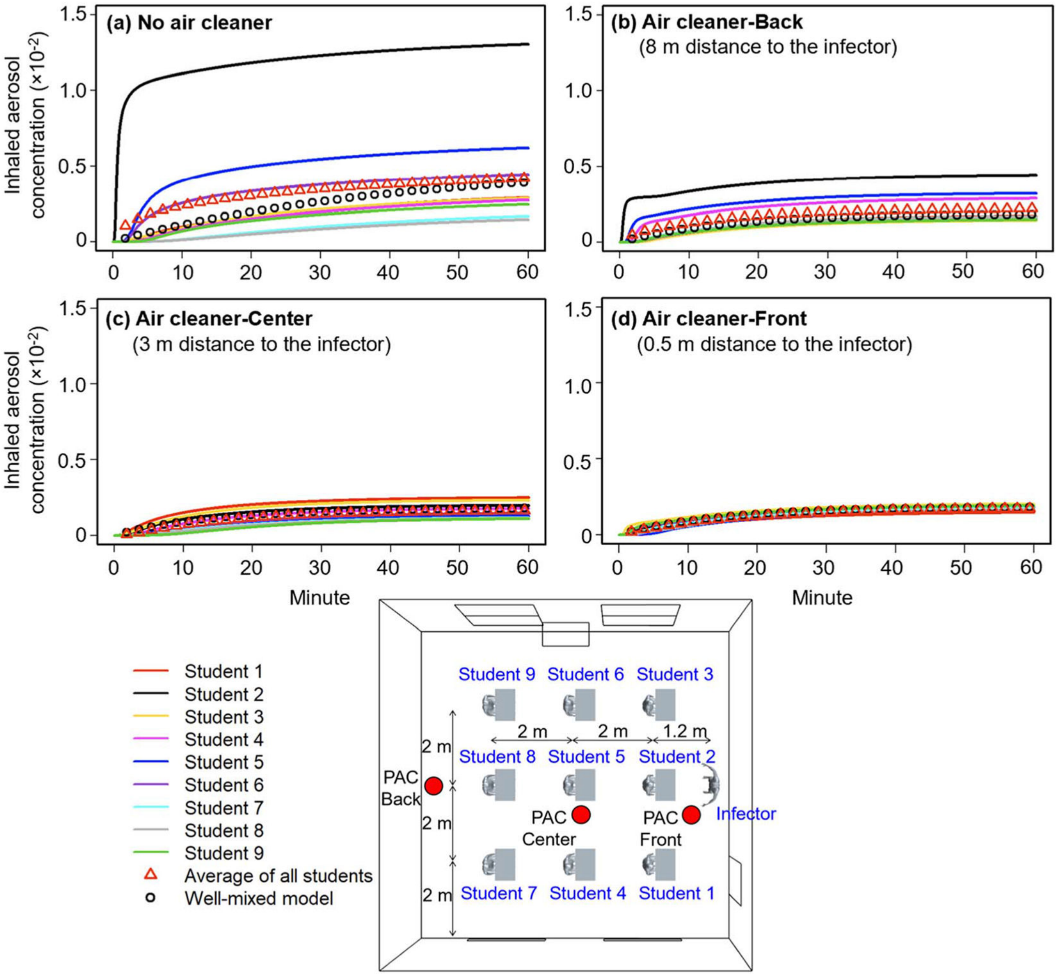

Fig. 6.

Transient inhaled aerosol concentration of nine students under displacement ventilation. Four scenarios of deployment of portable air cleaner are shown: (a) without air cleaner, and with a single air cleaner at (b) 8 m, (c) 3 m, and (d) 0.5 m distance to the infector. The simulation results are compared with the well-mixed mass balance model. The concentrations are normalized by emission concentration. PAC: portable air cleaner.

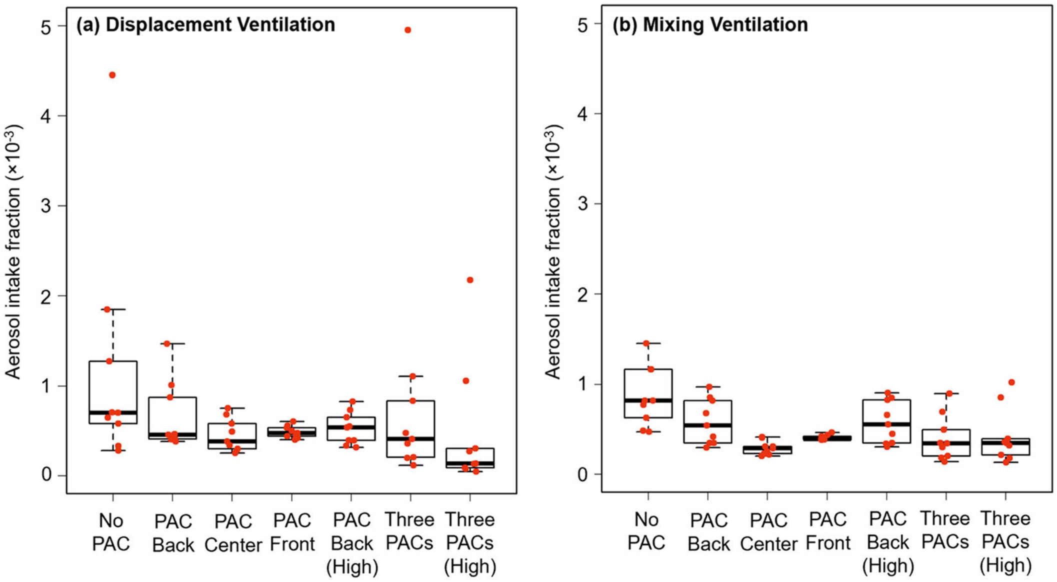

Fig. 7.

Aerosol intake fraction of students after 60 min simulation under (a) displacement ventilation and (b) mixing ventilation with seven arrangements of portable air cleaners (PACs): without PAC (No PAC); with a single PAC at the back (PAC Back), at the center (PAC Center), and at the front (PAC Front) of the room with a discharge height of 0.4 m; with a single PAC at the back of the room with a discharge height of 0.9 m (PAC Back High); with three PACs at the back, center, and front of the room, respectively, with a discharge height of 0.4 m (Three PACs); with three PACs at the back, center, and front of the room, respectively, with a discharge height of 0.9 m (Three PACs High). The total flow rate of three PACs is equal to the single PAC. The horizontal line within the box represents median value. Box extents are 25th and 75th percentiles. Whiskers show 1.5 × interquartile range if there are outliers, otherwise the maximum and minimum values. Red dots represent the intake fractions of different students.

Table 1

Summary of simulation cases and key simulation results (PAC: portable air cleaner; NADR: non-infectious air delivery rate; SD: standard deviation)

Case ID	Ventilation strategy	PAC number	PAC distance to infector (m)	PAC location in the room	PAC discharge height (m)	PAC face velocity (m s^{-1})	NADR (h^{-1})	Mean aerosol intake fraction of nine students ($\times 10^{-4}$) (SD)
1	Displacement	0	—	—	—	—	1.4	12.02 (13.12)
2	Displacement	1	8	Back	0.4	2	4	6.56 (3.79)
3	Displacement	1	3	Center	0.4	2	4	4.52 (1.84)
4	Displacement	1	0.5	Front	0.4	2	4	4.87 (0.67)
5	Displacement	1	8	Back	0.9	2	4	5.27 (1.82)
6	Displacement	3	8/3/0.5	Back/center/front	0.4	0.67	4	9.62 (15.30)
7	Displacement	3	8/3/0.5	Back/center/front	0.9	0.67	4	4.77 (7.08)
8	Mixing	0	—	—	—	—	1.4	8.64 (3.34)
9	Mixing	1	8	Back	0.4	2	4	5.86 (2.52)
10	Mixing	1	3	Center	0.4	2	4	2.93 (0.76)
11	Mixing	1	0.5	Front	0.4	2	4	4.05 (0.29)
12	Mixing	1	8	Back	0.9	2	4	5.81 (2.37)
13	Mixing	3	8/3/0.5	Back/center/front	0.4	0.67	4	4.01 (2.53)
14	Mixing	3	8/3/0.5	Back/center/front	0.9	0.67	4	4.25 (3.07)