Central HVAC Filtration vs. Portable Air Purifier Filtration

Mitigating COVID-19 In Public Spaces

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What can the hospitality industry do to reduce the risk of transmission of COVID-19? Part is recognizing that HVAC systems play a role in mitigating the risk of airborne transmission of COVID-19.[1] At the beginning of the pandemic, hospitality facilities, including hotels and restaurants, quickly aligned with guidance from the CDC,[2,3] WHO[4] and other credible organizations such as ASHRAE[5,6] by adjusting operating guidelines to increase outdoor air dilution and improve filtration, where possible, while maintaining guest and associate comfort. This article discusses a comprehensive study recently conducted by the authors to investigate the efficacy of portable air purifiers to improve air quality in public spaces.

Improving filtration can be accomplished by using filters with higher MERV ratings. For instance, high-efficiency particulate air (HEPA) filters are effective in removing "99.97% or better for all particle sizes."[7] However, filters with higher ratings may increase the pressure drop, which may make them impractical for some applications. And, even the most efficient filters in a centralized HVAC system potentially do not mitigate heavier droplets or other particles that do not get entrained into the return air vents and may float around a given space.

Increasing the amount of outdoor air the system delivers can further dilute particle concentration and transmission risks. However, outdoor conditions such as temperature, humidity and air quality can limit the amount of outdoor air that can be introduced while maintaining occupant comfort levels.

Building codes and regulations outline the requirements for ventilation, and hotel heating and air-conditioning systems are designed to meet these standards. However, they were not designed to increase this significantly. Also, hotel guest room heating and air conditioning systems should be designed with slight positive pressure, so air does not pass from one room to another.

Another way to increase the ventilation is by leveraging air purifiers to provide equivalent air exchanges

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through filtration and circulation. The EPA has stated, "Consider using portable air cleaners to supplement increased HVAC system ventilation and filtration, especially in areas where adequate ventilation is difficult to achieve."[8] One CDC example concluded that "adding the portable HEPA unit increased the effective ventilation rate and improved room air mixing, resulting in an 80% reduction in time for the room to be cleared of potentially infectious airborne particles."[9] Another study for a reception setting showed "high-volume HEPA filtering decreases [the individual risk of infection] by a factor of ten."[10]

For our comprehensive study, computational fluid dynamics (CFD) models such as the one in *Figure 1* were developed to simulate airflow patterns while people were breathing and talking in public spaces under normal conditions. Portable air purifiers were introduced into the models to analyze the benefits and determine their optimal number and locations. Field experiments using thermal mannequins were also carried out to validate and visualize the cleaning performance of portable air cleaners.

The overall goal was to improve air quality and mitigate airborne transmission risks in restaurants and public spaces with these three objectives:

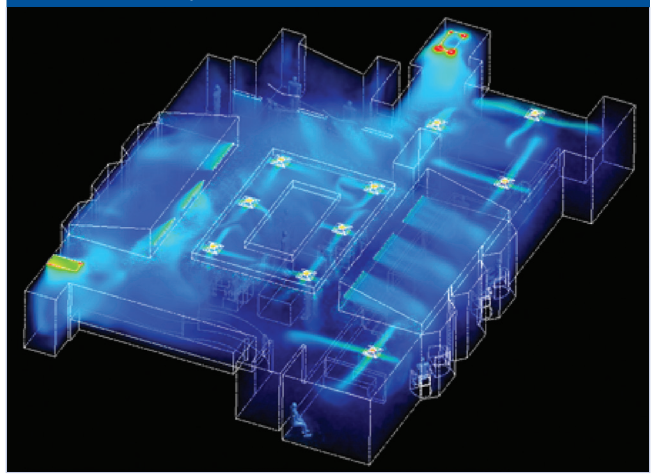
- Instill confidence in guests that they are safer in public spaces such as hotels so they will want to travel, and have associates feel safer about returning to work.
- Improve indoor air circulation and dilute concentrations of airborne contaminants.
- Remove harmful particles from the air where it is most important—where the people are.

Public Spaces in Hospitality

Hotel public spaces are designed primarily for aesthetics and function, especially in lobbies, restaurants and ballrooms. Architects and designers create these beautiful spaces with a lot of open space and high ceilings. Then they hand the drawings over to a mechanical engineer and ask them to make the spaces comfortable for the occupants; they do this by controlling the temperature and humidity. Hotel HVAC systems are not typically designed to give a perfect mixing of air, nor are they designed for zoning, isolation and pathogen control like hospitals.

Although hotel HVAC systems provide more air dilution for given contaminant sources due to both larger space volume and potential vertical air stratification, higher ceilings introduce larger volumes of air to condition and supply, and returns are further away from the occupant's breathing zone. Filtration and purification provided by the central system will have to overcome these challenges.

FIGURE 1 Layout of the lobby where the simulation is performed. It includes the furniture in the lobby with bar, lounge furniture, meeting table, reception desk and HVAC ducting. Supply air vents are represented with the airflow coming out from it. One at the top edge and another at left bottom corner vents with red color dots around it represents return air vents.



Without social distancing, ballrooms can have high occupant density, especially when the setup is for large meetings and conferences. And, the configuration of the space can change throughout the day. In the morning, the space can be set "in rounds" for breakfast, then changed to a classroom setup for the meeting that lasts throughout the day. Then it flips to a stand-up reception for the evening.

Restaurants have an added challenge, as the occupants will take their masks off to eat and will likely be talking to the people they are dining with. If an infected person is sitting among them, they can potentially introduce large numbers of infectious particles into the air.

Pros and Cons of Central HVAC Filtration Vs. Portable Air Purifier Filtration

Improving filtration can either be done at the central HVAC level or by using portable air purifiers in the space. Both options have their pros and cons.

Central HVAC Filtration

Any air filtration technology generally has at least the following two components: a fan to move the air and a filter medium to perform the filtration. Both exist in every central HVAC system. The only difference is that the regular low MERV-rated media filter has lower filtration efficiency, compared to a high MERV-rated or HEPA-grade media filter, for particles and microbes riding on particles, aerosols, etc. One of the simpler options is to change the HVAC media filter to a higher MERV-rated filter like MERV 13 or above that can filter out these contaminants and microbes with better effectiveness, depending on particle size, for example about 50% at 0.1 micron.

A limit exists to how much we can increase the efficiency of these filters, as the higher rated filters, if not selected properly, may restrict airflow and cause a reduction in air pressure. This in turn could compromise the comfort of occupants. Any such change to the media filter could call for more frequent filter change, causing increased recurring operational cost.

Pros

- Single point of intervention, no extra space requirement.
- Out of sight of occupants, not causing any aesthetic or acoustic nuisance in the space.
- No complex study needed to design or install.
- Minimal change to maintenance requirements.

Cons

- In-space effectiveness could be limited as the particles and aerosols still travel within the space before it is pulled down by gravity, collides into furniture or other surfaces (such as people), or are pulled into the HVAC return air vent.
- If a MERV filter is upgraded to a filter with a higher MERV rating, more frequent filter changes may be required, and there may be increased recurring operational cost.
- Since it is out of sight, there is no way for occupants to know what air quality improvement measures have been taken.
- For proper effectiveness, it requires well-installed filters without gaps to achieve the expected removal efficiency.

Portable Air Purifier

Like any air filtration technology, even a HEPA-based portable air purifier has a fan and a filter medium. The reason for the selection of a HEPA-based portable air purifier is its wide availability and reasonable price. A HEPA filter-based portable air purifier could comparatively do a better job overall for two reasons: 1) HEPA filters eliminate 99.97% of particles up to 0.3 micron, and NASA research suggests they are very effective at removing even submicron and nanoparticulate sizes as well.[11] 2) Portable air purifiers placed near people and positioned so their suction inlet faces toward people can effectively and quickly do the filtration within the space before the particles and aerosols spread around. This could be a better alternative, but, as with everything it has its pros and cons.

Pros

- Portable, plug-and-play and do not need any infrastructure alteration or special installation skill.
- HEPA filter is more effective than a MERV 13 filter at filtering even at submicron and nanoparticle size.
- To achieve the same level of particle removal, the HEPA filter takes less time compared to a MERV 13 filter.
- In-space placement could allow the purifier to be relatively more effective in reducing the spread further.
- Could add to a visual assurance of healthier space for occupants.

Cons

- Would take up usable space and wall outlets.
- Could be a nuisance for occupants due to noise when operating at high speeds.
- May require performing complex CFD study of airflow in the space prior to their installation to achieve optimum effectiveness.
- Could be switched off or moved by the users/occupants, making them ineffective in that area/space.
- Added maintenance to care for the air purifier units and change filters when needed.

Effective Placement of Air Purifiers

Detailed fluid dynamic models point to three key criteria in determining the best strategy for air purifier deployment.

1. The closer the infected person is to the suction inlet of the air purifier the higher the effectiveness. While intuitive, the speed with which small airborne fluid particles can diffuse in a room is a concern. Typical HVAC systems are designed to efficiently distribute air in spaces; therefore, the more time that elapses from when the fluid particles are emitted, the larger the spread radius of the particles. The droplets will generally move around the room until they are pulled down by gravity, collide into furniture or other surfaces (such as people),

FIGURE 2 Distribution of particles with no portable air purifier. The yellow figure represents the infected spreader.

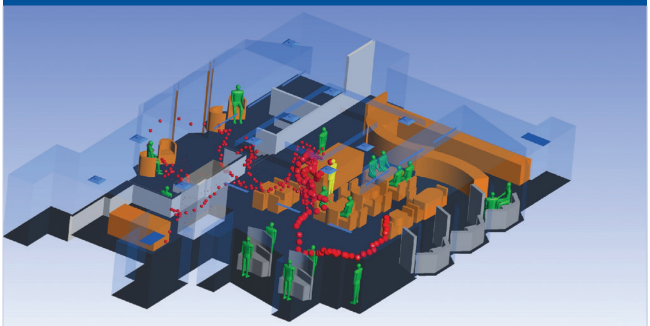
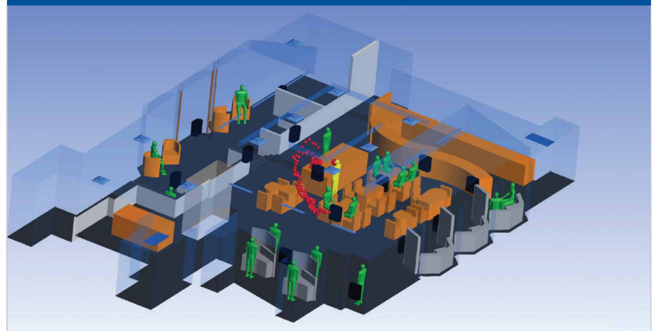


FIGURE 3 Distribution of particles with portable air purifier located adjacent to the seating area. The yellow figure represents the infected spreader.



or are pulled into the HVAC return air vent.

2. Based on the airflow patterns, HVAC supply and return vent locations, the shape of the room and other factors, there will generally be locations where the air is not well mixed or moved, creating a potential for areas with a higher concentration of fluid particles (*Figure 1,* page 29).

3. The height of the air purifier also has an impact on efficacy. When the air purifier is less obstructed, the device inlet can treat more air in a set amount of time. Experimentation shows that a purifier at tabletop level is more effective than one on the floor level.

At a steady state, a well-designed and well positioned, efficient air purifier can eliminate 99.97% of particulate matter of 0.3 µm particles within a space in less than an hour. When modeling a sneeze with an air purifier on the tabletop next to the subject, fluid analysis shows the air purifier is 80% effective in containing all the small and medium particles, while the remaining large particles were captured on the surface of furniture or pulled down to the carpet due to gravity within a relatively tight radius 1.8 m to 2.7 m (6 ft to 9 ft) of the subject (*Figure 2*).

Case Studies by Computational Fluid Dynamics Modeling

This study used a commercial computational fluid dynamics (CFD) tool to predict the airflow pattern and virus-carrying particle transport in a typical restaurant dining area within a hotel. Since indoor airflow is highly chaotic, a proper turbulence modeling method and model are critical for accurate flow prediction. This study used the steady-state RANS simulation method with the RNG k-epsilon turbulence model,[12] which were proven to be effective and suitable for indoor airflow simulation.[13] The transient trajectories of particles released from sources (e.g., mouths) were tracked using the software's discrete particle model, with the assumption of monodispersed noninteracting spherical particles.

TABLE 1 Restaurant specifications.

OBJECT	DIMENSIONS	CONDITIONS
Diffuser Inlet	1.22 m × 0.30 m	T_{in} = 17.6°C
Dining Table	0.87 m × 0.87 m × 0.75 m	Adiabatic
Exhaust Outlet	0.61 m × 0.61 m	T_{ex} = 20°C
Occupant	0.30 m × 0.43 m × 1.30 m	T = 27°C
Ceiling Light	–	10.7 W/m^2
Total Air Change Rate	–	5/h
Supply Air Velocity	–	0.3429 m/s

Due to the scarceness of virus particles in the space, the momentum impact from the particles to the air turbulence is negligible.[14] Multiple numerical grids were tested to ensure sufficient numerical accuracy and reasonable computing cost. Approximately 650,000 numerical cells were used for the CFD model, among which finer grids were allocated for the occupants and purifiers.

Case Description

A typical separate restaurant dining area in a hotel was modeled with the full dining capacity (177 people) and the designed HVAC conditions (locations, sizes and capacities) (as shown in *Figure 3* and summarized in *Table 1*).

A set of portable air purifiers were tested in the simulation with various combinations of model, capacity, number and layout. This article presents the results of using two types of commercially available air purifiers to demonstrate the influence of portable air purifiers (*Table 2*). Eight floor air purifiers (FAP) were arranged at both ends of the restaurant (five at one end and three at the other end) (*Figure 3*), which drew the room air from one side of the purifier and exhausted cleaned air from the top of the unit. One table air purifier (TAP) was placed at the center of each dining table, which drew the room air from the entire round side of the unit and exhausted the cleaned air from the top.

This study focused on talking—the main concern during dining and ballroom events. Studies showed that talking may release 2,600 droplets per second at a speed of 1 m/s to 5 m/s (197 fpm to 984 fpm).[15] The range of the total airflow rate from a mouth when speaking is about 284 cm^3/s to 759 cm^3/s (0.60 cfm to 1.61 cfm).[16] Using the average 500 cm^3/s (1.06 cfm) and assuming mouth opening area at 1.8 cm^2 (0.28 $in.^2$) leads to an average talking airflow speed of 2.77 m/s (545 fpm), which meets the particle image velocimetry test result at the order of 3.1 m/s (610 fpm).[17]

The study simulated multiple talking persons at different locations, while this article only presents the results from one "pollutant source" as shown in *Figure 3*. *Table 3* summarizes the simulated virus particle details. The number of virus particles released from the mouth was assumed as 5,000 to ensure that the deviation of the particle statistical results is less than 1%.[18]

Particles larger than 10 micron tend to drop quickly, while smaller particles tend to flow with air, and 3 micron represents a mean airborne particle size during talking.[19] Sensitivity studies were conducted in CFD, which indicates that particles with sizes less than 10 micron present good airborne behaviors; thus 3 micron particles were modeled.

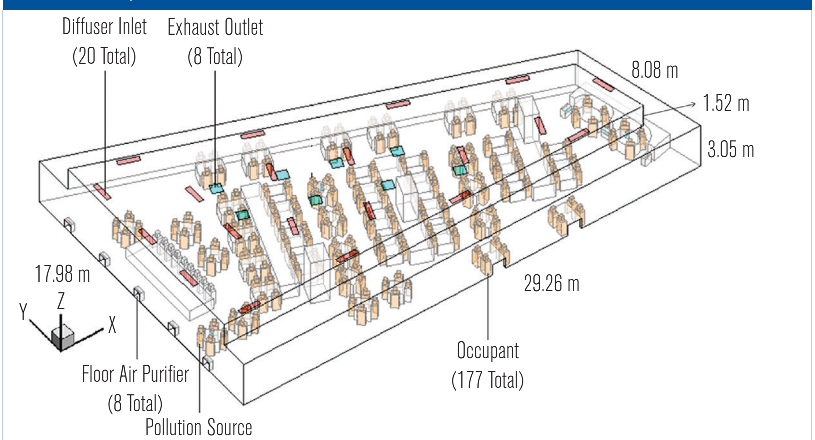
TABLE 2 Purifier specifications.

UNIT	FLOOR AIR PURIFIER	TABLE AIR PURIFIER
Dimensions	0.56 m × 0.33 m × 0.61 m	0.42 m × 0.2 m × 0.2 m
Inlet Size	0.1291 m^2	0.1935 m^2
Outlet Size	0.0452 m^2	0.0316 m^2
Clean Air Delivery Rate	0.156 m^3/s	0.056 m^3/s

TABLE 3 Particle release conditions.

OBJECT	VALUE
Open Area of Talking Mouth[16]	1.8 cm^2
Airflow Rate From Talking Mouth[20]	500 cm^3/s
Temperature of Airflow From Talking Mouth	27°C
Aerodynamic Diameter of Particle[21]	3 mm
Density of Particle[22]	600 kg/m^3
Number of Particles Released From Talking Mouth[18]	5,000

FIGURE 4 Computer model of a restaurant.



Performance Analysis of Different Ventilation Conditions

Indoor airflow patterns in public spaces such as restaurants are extremely complicated, influenced by many factors such as HVAC supply and return locations and conditions as well as indoor object layouts and adjacent space conditions. Occupant movement provides additional disturbance to the air distribution, which was not considered here—typical for system design/evaluation purposes. Note that occupant movements (e.g., the head direction swing during talking) can play an important role in actual contaminant dissipation.

The selected results illustrate the different performances under three ventilation scenarios: (1) central air-conditioning system (CA), (2) central air-conditioning system with floor air purifiers (CAF) and (3) central air-conditioning system with both floor and table air purifiers (CAFT). *Figure 4* shows the predicted air velocity vectors at the height of the breathing zone (Z = 1.1 m [3.61 ft] above the table with the virus carrier. The installation of portable air purifiers changes the flow directions as expected and mitigates the cross-table airflow that may cause the cross-infection. The table unit displays explicit and favorable air inflow toward the purifier. As a result, most of the particles released from the source mouth flow with the air and enter the purifiers (*Figure 5*). The strong upward outflow from the purifiers also helps move the particles toward the ceiling where the central HVAC exhausts are located.

Table 4 quantifies the ventilation performance by comparing the destination of particles. Numbers of particles that were, respectively, discharged from the central exhausts, or portable purifiers, or deposited on different surfaces were counted and computed in percentage (out of the total 5,000 particles released).

It is evident that if purely using the CA, only a small fraction of particles can be discharged through the ceiling exhausts. Most of the particles are spread out indoors and ultimately deposited on the occupants, tables, ground and walls. FAP can clean 28% of the particles while increasing the deposition (48%) on the surrounding walls due to the downward extraction flow to the units. TAP can handle almost 80% of the particles, while slightly increasing the deposition on the tables compared to floor units (but is better than the CA), indicating a promising performance.

Similar CFD simulations were conducted for a large ballroom with more occupants (1,320) and round tables (165), which demonstrated similar performance. Due to more complex indoor airflows and relatively larger table size, finding proper TAP (both size and capacity) is critical to achieve a successful cleaning solution.

FIGURE 5 Airflow vectors at the breathing height (Z = 1.1 m) under different ventilation conditions: (a) central air-conditioning system (CA); (b) central air-conditioning system with floor air purifiers (CAF); (c) central air-conditioning system with both floor and table air purifiers (CAFT). Square represents occupant. Circle represents table purifier at the table center.

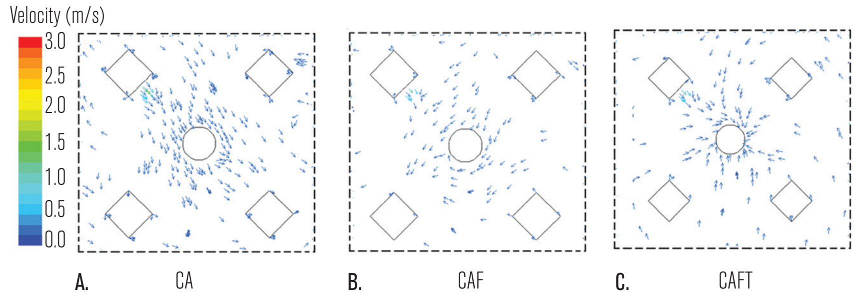


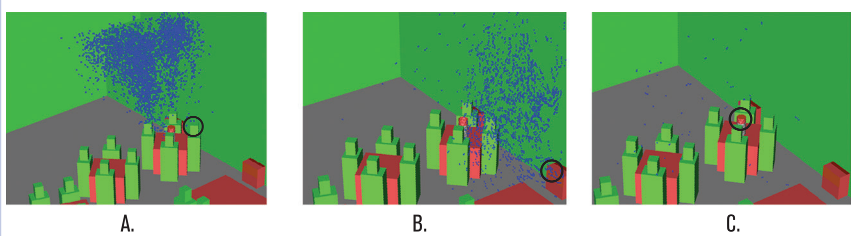
TABLE 4 Particle fate comparison.

	Ventilation Mode	CA (%)	CAF (%)	CAFT (%)
Discharged	Central Exhausts	3.26	2.02	1.62
Removed	Floor Air Purifier		28.08	1.42
	Table Air Purifier			76.40
	Occupant Body	32.64	4.10	1.72
Deposited	Table	25.08	6.48	13.18
	Ground	24.82	5.70	1.46
	Surrounding Wall	11.36	48.04	1.58
	Ceiling	2.84	5.58	2.62
	Total	100.00	100.00	100.00

Case Studies by Field Experiment

A field mock-up experiment was conducted in a typical hotel restaurant and ballroom in December 2020. Four heated thermal mannequins at 65 W (220 Btu/h) were built and placed to represent actual occupants, each of which had a body temperature of 31°C (88°F) at the forehead and 28°C (82°F) at the clothed body that matched the body temperatures of actual persons tested in the same space. Water-glycerin solution-based fog was generated and supplied through the mouth of one mannequin to simulate both the coughing and talking scenarios. The coughing action lasted for five seconds with the droplet/fog exhaling speed around 5 m/s (1,000 fpm), while the talking lasted for 20 seconds with the exhaling speed of 1 m/s (200 fpm). The exhaling speed was on a par with the CFD simulation, while CFD released all particles at 1 second. The sizes of the exhaled particles/droplets were mostly (over 70%) in the range of <$PM_{2.5}$, which are readily airborne.

FIGURE 6 Particle trajectories at t = 30 s after the release under different ventilation conditions: (a) CA; (b) CAF; (c) CAFT. Black circle in (a): source occupant; (b): floor purifier; (c): table purifier.

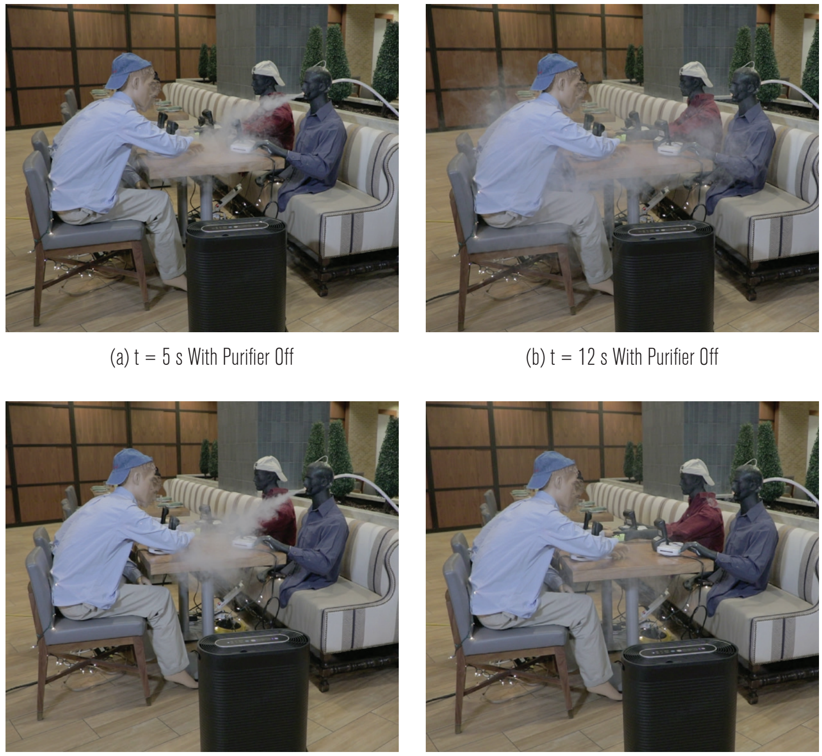


The transient dissipation pattern of the contaminant was professionally videotaped, and the particle concentrations at key occupant locations were measured with several particle counters and sensors. The experiment tested both the base case under common room conditions without air purifiers and the cases with a variety of air purifier types and locations to verify and compare the performance of air purifiers.

Restaurant

Figure 7 shows the comparison of the contaminant distributions around the occupants in the dining setting in a restaurant, at t = 5 s and t = 12 s, respectively, after the cough started, without and with using the floor air purifier (at 560 m^3/h [330 cfm]). The particles, which otherwise would be moving around the space for an extended period of time (depending on the relative location of contaminant source and supply and return outlets of the central air-conditioning system), can be quickly and effectively removed by the purifier.

FIGURE 7 Contaminant distribution in the dining setting in a restaurant.

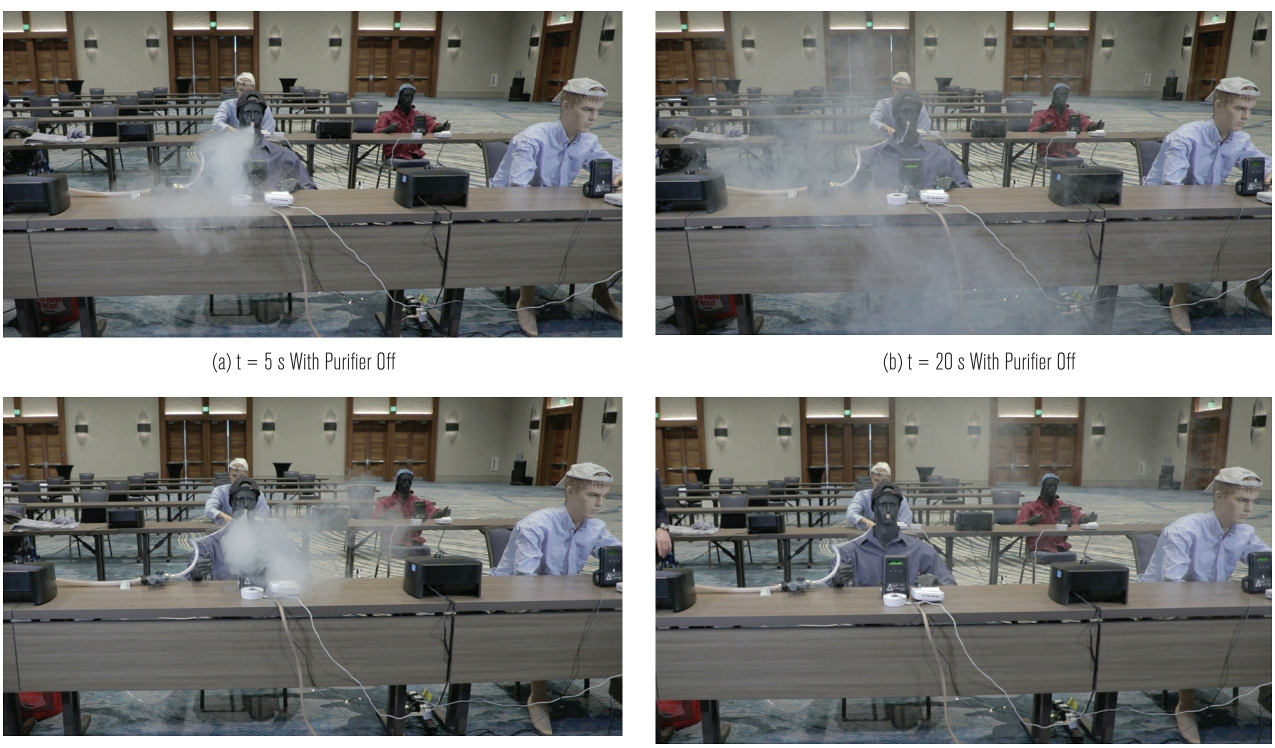


(a) t = 5 s With Purifier Off
(b) t = 12 s With Purifier Off
(c) t = 5 s With Purifier On
(d) t = 12 s With Purifier On

Ballroom

Both the classroom and banquet settings in a large ballroom were tested. *Figure 8* presents the contaminant distribution without and with using the TAP (at 114 m^3/h [67 cfm]), under the classroom setting, respectively, at t = 5 s and t = 20 s after the cough started. With the conventional HVAC systems, the contaminant showed a strong movement in the space and might transfer through multiple front and back rows depending on the source location in the space. The air purifier, placed between every two

FIGURE 8 Contaminant distribution in the classroom setting in a ballroom.



(a) t = 5 s With Purifier Off
(b) t = 20 s With Purifier Off
(c) t = 5 s With Purifier On
(d) t = 20 s With Purifier On

occupants, was able to contain the contaminant within the source premises and remove the contaminant in a timely manner. Similar dispersion patterns were observed for the banquet case. However, due to the size of the banquet table and occupant density in the banquet setting, air purifiers with proper inlet/outlet locations and flow rate need be further identified.

Conclusions

This research shows that using portable air purifiers with HEPA filtration is an effective method to improve air quality and to help mitigate airborne transmission of pathogens. HEPA filtration is a proven technology that is effective in removing 99.97% of harmful particles from the air. They provide additional equivalent air exchanges, which can reduce risk of transmission.

Installing portable air purifiers can be as efficient as more elaborate solutions. They are easy to install and require no modification of the existing heating and air-conditioning system. They are flexible and can be redeployed as needs change. The cost of filters, maintenance and energy should also be considered for any solution including portable air purifiers.

Modeling studies demonstrated the most effectual approach is to place the filtration as close to people as possible. The intake and discharge of the units should also be considered. Our studies used units with side intake and top discharge. Units should not discharge directly toward a person. Optimal location of portable air purifiers will be in proximity to where people are seated, congregate or queue, where they spend extended periods or where adequate social distancing is difficult. Examples include public space areas such as lobbies, meetings spaces, restaurants, bars and check-in areas. They are also ideal for areas like locker rooms, break rooms, cafeterias and meeting rooms.

An additional benefit is an overall improvement of air quality by removing dust, dander, pollen, smoke and other particles that are problematic for those with allergies or asthma. However, each space is unique and needs to be assessed and addressed individually.

Acknowledgments

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