Reducing Airborne Particulates Using Displacement Ventilation

BY RYAN JOHNSON, MEMBER ASHRAE; CHRIS BURROUGHS, ASSOCIATE MEMBER ASHRAE

Stratified air systems are a style of air distribution shown to improve air quality and energy savings compared to traditional overhead mixed air ventilation systems. Their initial popularity in industrial spaces stemmed from the systems' ability to reduce the amount of unhealthy airborne chemicals and particulates in the breathing zone. This article reviews new research that compares the behavior of airborne particulates (0.3 µm – 5.0 µm) generated by an occupant in a typical office environment when ventilated with a stratified air system and a traditional overhead mixed air system. The particle count measurements were then compared to an equivalent tracer gas test (CO_2) and a computational fluid dynamics (CFD) model to determine how closely they match the particulate behavior.

What Is a Stratified Air Distribution System?

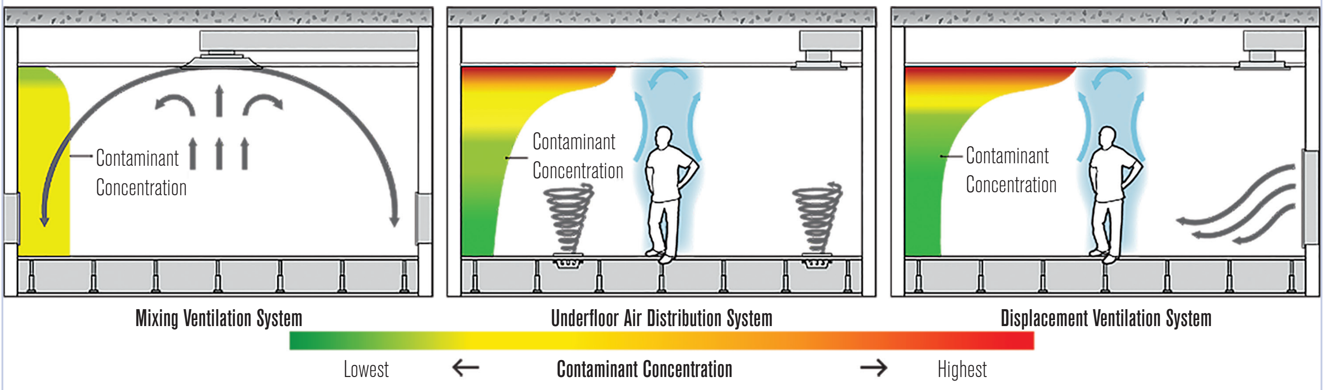
Stratified air distribution systems create a comfortable environment by providing low-velocity supply air in cooling mode. The supply air temperature is closer to the room setpoint than it is to the temperature of the air discharged by traditional systems, including mixing ventilation (MV).

This air delivery approach relies on natural convection to move the air through the space, making the system energy efficient. In stratified air systems, heat generated from sources such as people and computers naturally pulls supply air throughout the space where it is needed. Comparatively, a traditional MV system requires increased fan energy to push the air at a higher pressure and greater temperature difference from the ceiling, requiring more energy to condition the space (*Figure 1*). Additionally, in a stratified system, natural convection generates thermal plumes that carry contaminants and particles upward out of the breathing zone, resulting in improved air quality.

The air quality benefits of stratified air systems are often quantified using zone air distribution

Ryan Johnson is research and development manager and Chris Burroughs is manager for sustainable systems at Price Industries, Inc., in Atlanta.

FIGURE 1 Typical cooling airflow patterns and contaminant distributions in a mixing ventilation system (left), underfloor air distribution system (middle) and displacement ventilation system (right).



effectiveness (E_z), which is the ratio of the air contaminant concentration between the room air and the return air. ASHRAE Standard 62.1-2022, *Ventilation and Acceptable Indoor Air Quality*, codifies overhead mixed air systems as having a maximum E_z of 1.0 with a ceiling supply of cool air, meaning the air that occupants breathe has the same number of contaminants as the air exhausted from the space. Stratified air systems typically have an E_z of 1.2–1.5 depending on their configuration, and research has shown them to achieve upward of 2.0 (*Table 1*).

Additional design considerations need to be considered for spaces that require heating to minimize the impact on IAQ. DV systems are commonly combined with fin tube heat exchangers, radiant panels and other supplementary systems in spaces that require significant heating.

State of the Industry and Stratified Systems

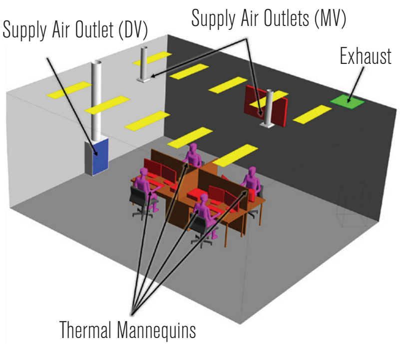
Most studies on air distribution effectiveness over the last 20 years have relied on tracer gases such as SF_6 or CO_2, as outlined in ASHRAE Standard 129-1997 (RA 2002), *Measuring Air-Change Effectiveness*. Previous research using tracer gas has been conducted comparing a traditional MV system to a DV system installed in a patient room. One field study showed that DV at half the airflow rate provides similar air-quality levels in the breathing zone to those of MV.[1] Comparable results were discovered in an in-situ study analyzing particle concentrations and overall exposure potential of a DV system and the relationship between the caregiver and patient location as the particulate source. The DV system resulted in equal or less exposure to the caregiver, using 33% less airflow than a MV system.[2]

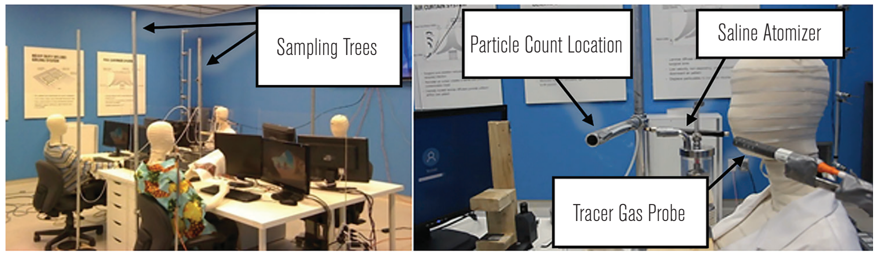
In recent years there has been renewed focus on the movement of particulates in the built environment. There is nuance in the airborne behavior of particulates

TABLE 1 Results from studies reviewing air distribution effectiveness (E_z) of mixing ventilation and stratified air systems with supply of cool air.

STUDY/STANDARD	LOCATION OF MEASUREMENT	AVERAGE MV E_z	AVERAGE DV E_z	AVERAGE UFAD E_z
Lee, Jiang and Chen[3]		–	2.5	2.1 – 2.4
Zhang[4]		–	–	1.1 – 1.2
Jung & Zeller[5]	In–thermal plume of standing person	0.95	1.22	1.47
	Out–thermal plume of standing person	0.94	1	1.13
	In–thermal plume of sitting person	0.96	1.68	2.01
	Out–thermal plume of sitting person	0.97	1.44	1.79
Badenhorst[6]	In front of standing person	0.88 – 0.97	1.2 – 1.6	1.2 – 1.6
	In front of seated person	0.90 – 0.97	1.3 – 1.95	1.3 – 2.0
Breum & Orhede[7]	Occupant workstation	0.8	1.4	–
Brohus[8]	Seated person	–	1.44 – 1.65	–
	Standing person	–	1.54 – 1.84	–
Helenius, et al.[9]		0.8 – 1.3	1.1 – 1.9	–
ASHRAE[10]		1.00	1.2 – 1.5	1.05 – 1.5

FIGURE 2 (LEFT) Layout of the environmental chamber showing locations of mixing ventilation and displacement ventilation diffusers. FIGURE 3 (RIGHT) The test room and saline solution atomizer.





(<100 µm), and their path depends on several variables, including particle diameter, relative humidity, gravity, thermal gradients and Brownian motion, with droplet evaporation playing a significant role.[11,12] This behavior calls into question whether the E_z measured from tracer gas tests accurately characterizes the behavior of particles.

Test Method

In a recent study, the authors' firm tested how DV and MV systems manage the distribution of particles of varying sizes within a typical office space (23 ft × 19 ft × 9 ft [7 m × 5.7 m × 2.7 m]). The test room was configured with four seated occupants at a desk; one mannequin was equipped to emit particulates near its mouth, and sensor trees were used to measure particulates in several other locations throughout the room. Both a traditional overhead mixed air system and a low-wall displacement stratified air system were installed in this room and were used to ventilate the space at various cooling loads (*Figures 2* and *3*).

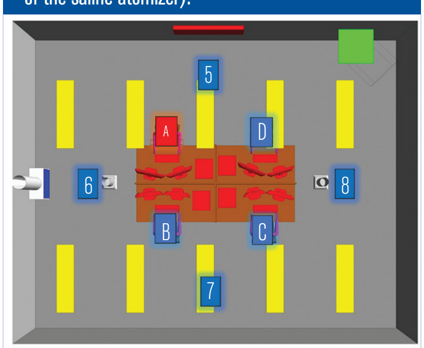
Two air outlets were used in the MV for improved air distribution since research has shown a single air outlet has a greater risk of creating stagnant zones in MV.[13] A computational fluid dynamics (CFD) model was developed in parallel with the lab test to verify the path of particles through the rest of the room.

A low-flow, four-jet saline atomizer with 0.9% saline solution was used to introduce particles ranging from 0.3 µm to 5.0 µm into the space. These airborne particles were introduced at the mouth of Mannequin A. Particle counts were measured at four locations throughout the room (5, 6, 7 and 8 in *Figure 4*) and at the two breathing zones of the mannequins (A, B, C and D in *Figure 4*, measured 43 in. and 67 in. [1092 mm and 1702 mm] above the finished floor). Two handheld particle counters in combination with constructed sampling trees were used to measure the particle concentrations throughout the space (*Figure 3*).

Multiple ventilation rates were compared for the MV and DV systems (2 ACH, 4 ACH and 6 ACH). Heating loads in the space were selected to simulate common occupancy scenarios, and the supply air temperatures were selected to maintain thermally neutral, steady-state conditions between measurements (*Table 2*). All the supply air was HEPA-filtered to ensure no additional contaminants were introduced into the space during testing. The room's ventilation system ran for several hours between tests to reset the background particle concentration. A thermal camera measured surface temperatures to ensure that room envelope conditions were identical between tests.

The data analysis of this experiment consisted of three steps: 1) measuring the E_z of these systems by applying calculations outlined in ASHRAE Standard 62.1-2022 on the particle counts, 2) measuring the air change effectiveness of these systems by applying the method outlined in ASHRAE Standard 129-1997 using a CO_2 tracer gas and 3) building a CFD model to compare the

FIGURE 4 Measurement locations (5, 6, 7 and 8 are measurement tree locations; A, B, C and D are thermal mannequin locations; Location A is the location of the saline atomizer).



results and to predict room behavior in other scenarios.

First, E_z (air distribution effectiveness) was calculated in this study as:

$$E_z = \frac{C_e - C_o}{C - C_o}$$

where C_o, C_e and C are the particle concentration in outdoor air, at the exhaust and in the breathing zone, respectively. A perfectly mixed room results in an E_z value of 1.0. A greater E_z value indicates cleaner air in the breathing zone. This value was calculated at the breathing zone of Mannequins B, C and D (at 43 in. and 67 in. [1092 mm and 1702 mm] above the floor).

Second, an air change effectiveness test was performed in parallel with the particle count test. CO_2 was used as a tracer gas injected in the supply duct. The CO_2 concentration was measured over time at the return grille and at multiple locations in the room. In this study, air change effectiveness was calculated as:

$$\text{Air Change Effectiveness} = \frac{A_{\text{Return}}}{A_{\text{Room,Average}}}$$

where A is the "age of air," a measure of elapsed time for the supply air to saturate a specific location of the room. A perfectly mixed room results in an air change effectiveness value of 1.0 since the supply air would reach the return as quickly as it reaches any other location of the room, on average. Higher air change effectiveness values indicate cleaner air in the breathing zone.

Often, the terms "air change effectiveness" and "air distribution effectiveness" (as well as "ventilation effectiveness") are used interchangeably in the HVAC industry, but they are in fact calculated differently. In this study, both values were measured to see how comparable they actually are.

Third, this investigation used a commercial CFD program to simulate the airflow pattern and particle distribution in the office under the same conditions. CFD is a powerful tool for modeling air movement in HVAC applications in the absence of physical measurements. Validating the CFD model with experimental data lets us confidently expand the model to other room sizes, room configurations, ventilation rates and applications for future particle count studies. The results of this study's CFD model have since been published in an academic journal.[14]

TABLE 2 Air supply temperature for the two ventilation systems.

SYSTEM	AIR CHANGE RATE	AIRFLOW (cfm/ft²)	THERMAL LOAD (Btu/h·ft²)	SUPPLY AIR TEMPERATURE (°F)		
				MV DIFFUSER (LEFT)	MV DIFFUSER (RIGHT)	DV DIFFUSER
MV	2 ACH	0.3	8.6	56.1	54.8	N/A
	4 ACH	0.6	11.7	55.3	54.5	N/A
	6 ACH	0.9	11.7	61	61.1	N/A
DV	2 ACH	0.3	8.6	N/A	N/A	57.0
	4 ACH	0.6	11.7	N/A	N/A	62.0
	6 ACH	0.9	11.7	N/A	N/A	67.0

Test Results and Discussion

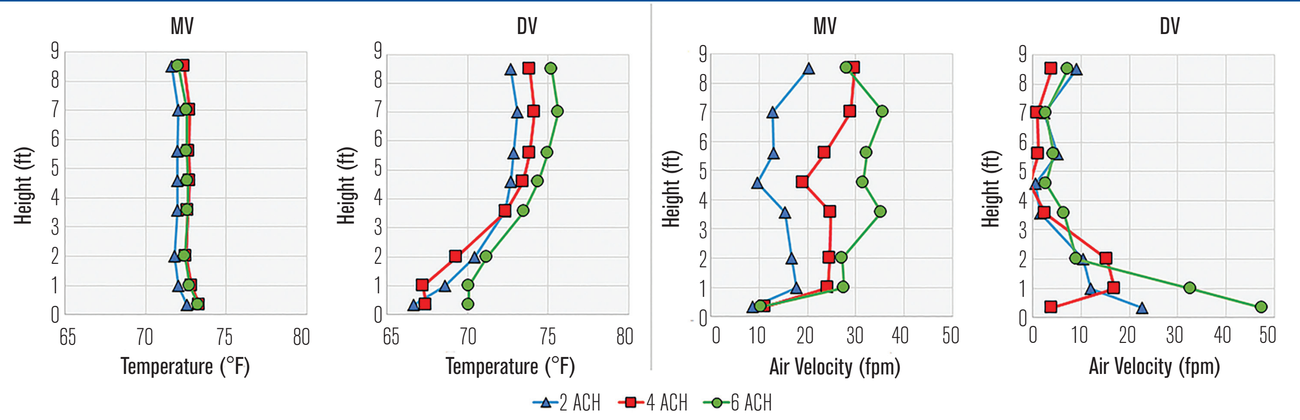
How Did the Room Behave Thermally?

The temperature and velocity profiles of the test room (*Figure 5*) matched industry expectations for typical MV and DV systems. The MV temperature profile was uniform from floor to ceiling for all three locations, and the MV velocity profile was similarly uniform but varied by airflow rate. The DV system demonstrated temperature stratification from floor to ceiling, and the DV room air velocity was much lower throughout the room except for at the floor since the supply air travels low to the ground to reach the heat sources. These temperature and velocity measurements provided a baseline validation that the ventilation systems behaved as intended at a thermodynamic level.

How Did the Particle Distribution Differ Between Displacement and Mixed Ventilation Systems?

The seated occupants in the DV system test were exposed to lower particle densities at their breathing zone (B, C and D, measured 43 in. [1092 mm] above the floor) relative to the MV system at the same ventilation rates (34%, 76% and 58% average particle count reduction for 2 ACH, 4 ACH and 6 ACH, respectively). The stratified air layer began just above the heads of the occupants. The particle counts in the DV tests were noisy, resulting in a wide variance in the final calculated E_z values of the space (*Figure 6*). In the 2 ACH test,

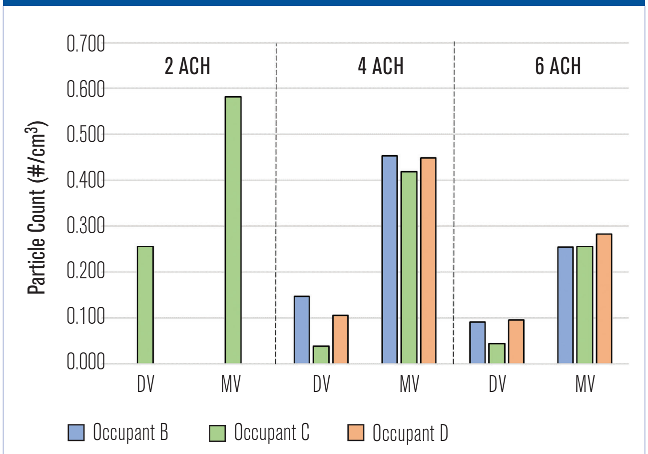
FIGURE 5 Comparison of temperature and velocity profiles of mixing ventilation and displacement ventilation systems as measured at Tree Location 7.



two thermal mannequins (B and D) and the associated desk equipment were powered off to maintain a heat balance in the space.

Further from the occupants (Trees 5, 6, 7 and 8), the difference in air quality between the MV and DV systems was inconclusive. The DV system maintained low particle counts at seated head height (43 in. [1092 mm]) but showed higher particle counts, and a similar E_z as the MV system, at standing height (67 in. [1702 mm]). It is important to note that there were no mannequins near these measurement trees nor any heat sources at standing height; thus, there was no thermal plume to pull the fresh supply air to these tree locations or to a higher level in DV. In MV, the particle counts remained mixed along the vertical axis. In both MV and DV, there was a wide variance in particle counts between the four trees, so it was challenging to make a direct comparison of the E_z values.

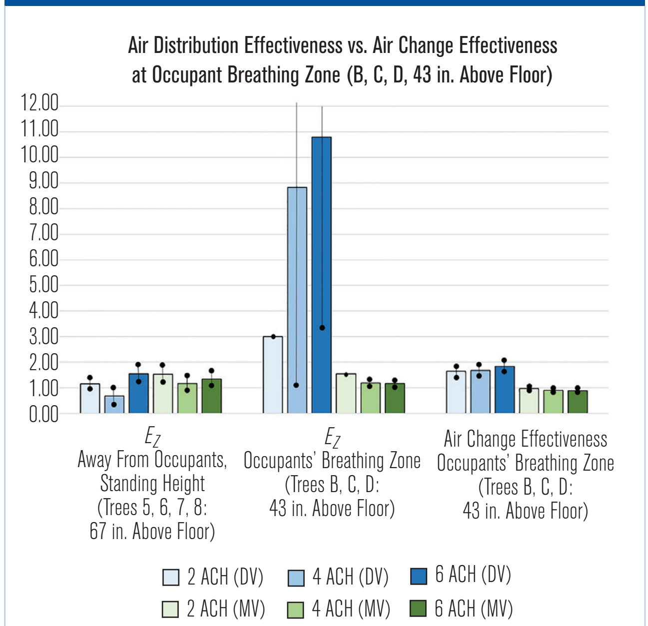
FIGURE 6 Particle density at the breathing zone of Occupants B, C and D at each ventilation rate. (Occupants B and D were removed for the 2 ACH condition to maintain heat balance in the room.)



Did the Air Change Effectiveness (CO_2 Tracer Gas) Match the Air Distribution Effectiveness (Saline Particle Count)?

The measured air change effectiveness values closely matched the findings of previous tracer gas studies (*Figure 7*). The MV system resulted in air change effectiveness values just below 1.0 for all measured heights. The DV system resulted in air change effectiveness values ranging from 1.6 to 1.8 depending on height. This

FIGURE 7 Comparison of measured air distribution effectiveness (E_z) and air change effectiveness; both values were taken as an average of measurements at the breathing zones of mannequins B, C and D.

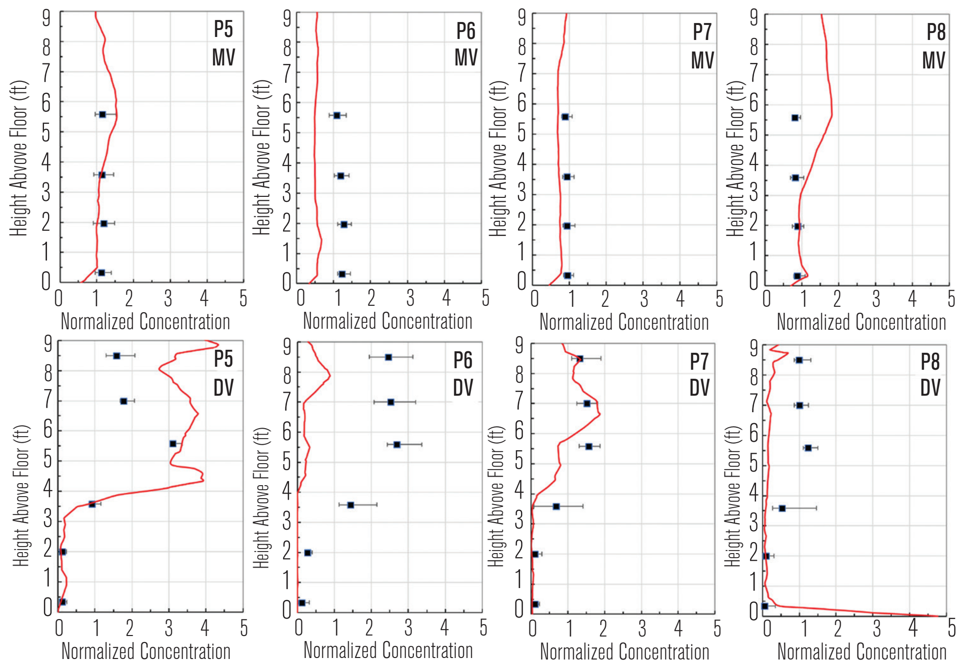


further validated that the room's aerodynamic behavior was typical of industry expectations.

There was not a 1:1 match between air change effectiveness and E_z at the occupant breathing zone. The E_z values were much higher in DV and reached average values upward of 8 to 10, with great variance between occupants.

This could be because the tracer gas was delivered to the room from the supply duct while the saline particles were delivered at the mouth of Mannequin A, resulting in a shorter path for the particles to reach the exhaust. However, both air change effectiveness and E_z trended in the same direction for all tests. This implies that air change effectiveness is a helpful predictor of E_z, but that air change effectiveness and E_z cannot reliably be used interchangeably.

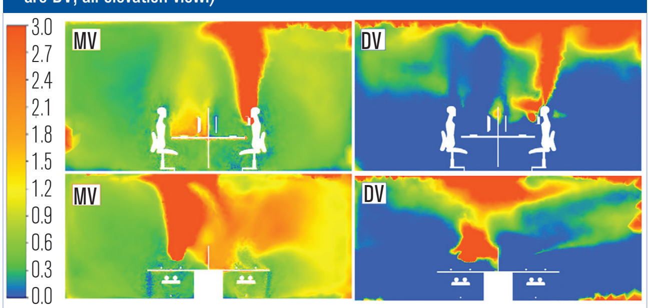
FIGURE 8 CFD prediction of particle density (red line) compared to experimental measurements in the test room (blue squares) with the mixed and displacement ventilation systems at a 4 ACH ventilation rate. The displacement ventilation particle count was more challenging to predict due to lower room air velocity.



Did the CFD Model Accurately Predict Particle Distribution?

The CFD analysis (*Figure 8*) was a reasonably accurate prediction of the particle concentrations of the experimental mock-up. It, too, had trouble predicting the exact behavior of the particles in the DV system, sometimes resulting in much higher or lower concentrations at different locations than the particle counters recorded in the experimental mock-up. This variability was primarily due to limitations in the CFD program's ability to predict the behavior of the lower room air velocity of the DV system. Otherwise, the overall picture was the same: MV resulted in a well-mixed distribution of particles, and DV resulted in a stratified distribution of particles. The resultant local E_z of the CFD followed the same trend as the physical mock-up. The CFD contours for the MV case indicate that the desk barriers create a stagnant area at the workstation across from the infected person (*Figure 9*). Further research might be needed to understand the impacts of various workstation designs and stagnant zones generated from barriers.

FIGURE 9 CFD contour plot of the particulate counts (normalized concentration) in the test chamber at 4 ACH ventilation rate. (Left images are MV; right images are DV; all elevation view.)



Conclusions

Within the last two years, we have seen a reprioritization in building design, with air quality moving to the top of the list. Several proven methods to improve air quality and reduce airborne particulates have been implemented in existing buildings, such as upgrading air handlers with MERV 13 or HEPA filtration, increasing ventilation rates, increasing total air changes per hour and installing unitary filtration equipment at the room level. This study points to another solution for future-proofing the workspace to improve air quality while minimizing impact on operating costs. This study shows that DV delivers fresh supply air directly to occupants in an interior cooling space, bypassing unoccupied areas and forcing undesirable particulates up to the ceiling. The design community should consider stratified air systems as an additional method for optimizing indoor air quality when designing buildings in the future.

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