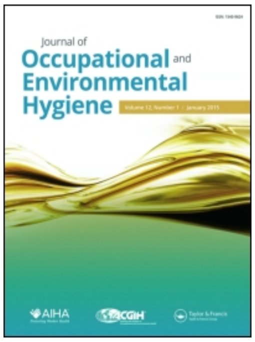

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Performance evaluation of mobile downflow booths for reducing airborne particles in the workplace

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ABSTRACT

Compared to other common control measures, the downflow booth is a costly engineering control used to contain airborne dust or particles. The downflow booth provides unidirectional filtered airflow from the ceiling, entraining released particles away from the workers' breathing zone, and delivers contained airflow to a lower level exhaust for removing particulates by filtering media. In this study, we designed and built a mobile downflow booth that is capable of quick assembly and easy size change to provide greater flexibility and particle control for various manufacturing processes or tasks. An experimental study was conducted to thoroughly evaluate the control performance of downflow booths used for removing airborne particles generated by the transfer of powdered lactose between two containers. Statistical analysis compared particle reduction ratios obtained from various test conditions including booth size (short, regular, or extended), supply air velocity (0.41 and 0.51 m/s or 80 and 100 feet per minute, fpm), powder transfer location (near or far from the booth exhaust), and inclusion or exclusion of curtains at the booth entrance. Our study results show that only short-depth downflow booths failed to protect the worker performing powder transfer far from the booth exhausts. Statistical analysis shows that better control performance can be obtained with supply air velocity of 0.51 m/s (100 fpm) than with 0.41 m/s (80 fpm) and that use of curtains for downflow booths did not improve their control performance.

KEYWORDS
Downflow booth; engineering controls; exposure prevention; particle reduction

Introduction

Exposure to airborne particles in the workplace can present a significant risk to worker health. Many processes in industry can expose workers to a wide variety of airborne particles. To reduce worker exposure to hazards, exhaust ventilation systems are commonly used to remove the contaminants generated by the tasks or processes. Exhaust ventilation is classified into two groups: the local exhaust system and the general exhaust system.[1] The local exhaust system is the preferred control method because it can remove contaminants by capturing them at or near the source. Local exhaust systems are comprised of up to four basic components including the hood, duct, air cleaning device, and fan. The general exhaust system can be used as dilution ventilation for contaminant control by mixing large quantities of outdoor air with the contaminated air. General exhaust is only advisable when contaminant concentrations and toxicity are low.

The downflow booth is an engineering control used to contain airborne particles by providing unidirectional filtered airflow from the ceiling, entraining released particles away from the workers' breathing zone, and delivering contained airflow to a lower level exhaust for removing particulates by filtering media. A recirculation downflow booth is designed to protect workers from breathing unsafe levels of particulates during material handling operations. Air flows from the booth ceiling, down across the operator's head, and into a grill below the operator's waist level, thereby drawing particulates away from the operator's breathing zone. The unidirectional or "push and pull" airflow pattern maintained by downflow booths has been shown to be effective for reducing worker exposure to hazardous materials across a range of industries including pharmaceuticals, chemical manufacturing, and food processing.[2] Downflow booths are often used for operations generating airborne particles, such as dispensing, filling containers, and sampling for product quality control. They can also be used to control vapors from processes if they are operated without air recirculation and fitted with appropriate explosion proof

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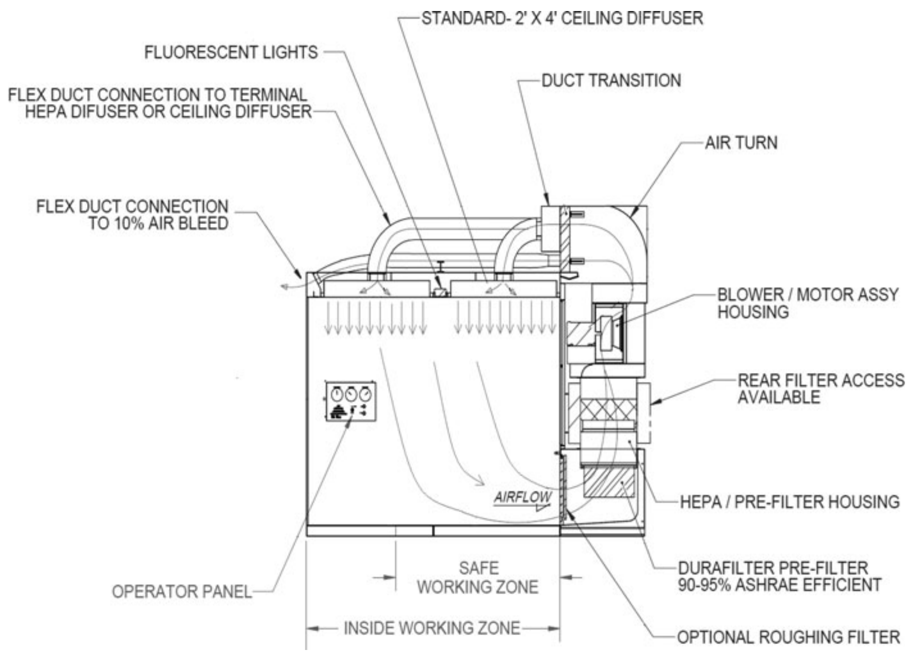


Figure 1. Typical downflow booth. The safe working zone is typically two thirds of the depth of the downflow booth.

features. Alternatively, they can be fitted with sorbent bed filters that could remove vapors.

As shown in Figure 1, the typical downflow booth has three walls and a ceiling; the front is open for operator access. The exhaust air plenum assemblies, including pre-filters in the bottom plenum, HEPA (High Efficiency Particulate Air) filter housings, and motor/blower assemblies are mounted behind the rear wall. Clean supply air is delivered from the ceiling to the operator working area (booth), and contaminated air is moved into the exhaust air plenum through return air grilles at the bottom of the rear wall. The return air is then drawn through primary slide-out prefilters, HEPA filters with bag-in/bag-out filter housings, the recirculation fan, the supply air manifold, and distributed to ceiling terminal diffusers and discharged through the ceiling. As shown in Figure 1, the safe working zone is defined by the design to reduce contaminant concentrations to safe levels and is dependent upon the specific dimensions of the booth.[3,4] The safe working zone is typically two thirds of the depth of the downflow booth. Bleed air is discharged to the suite through a diffuser on the front of the supply air manifold. Roughly 90% of the air is re-circulated; the makeup air (10%) is drawn into the front of the booth from the room. Therefore, the booth operates at a slightly lower pressure than its surroundings.

Downflow booths are capable of controlling exposure risk to hazardous materials (e.g., chemicals and drugs) for a wide variety of tasks and processes.[2] When using lactose as a surrogate test material to simulate the task of manual transfer of dry powder, typical containment performance provided by a standard downflow booth is able to maintain worker exposure levels below 100 micrograms of lactose per cubic meter ($\mu g/m^3$) over an 8-hr Time Weighted Average (TWA).[5,6] Combined with additional control measures (such as process area barrier curtains and ventilated enclosures) between the worker and the source of dust particles, Floura and Kremer have shown that downflow booths can even decrease worker exposures to airborne lactose below 1 $\mu g/m^3$ under ideal laboratory conditions.[3] For typical work environments, downflow booths can keep particle concentrations in the 50–100 $\mu g/m^3$ range.[3] Field tests have indicated that other control measures (a ventilated enclosure for transfer of engineering nanomaterials in this case) can be improved when implemented in a downflow room.[7] The downflow ventilation appeared to create a relatively stable environment for handling nanomaterials, because it did not promote the formation of eddies which can transport airborne particles directly into the worker's breathing zone (WBZ). Besides, air flows from the ceiling avoid the creation of a wake cavity recirculation region that could be formed by air flows from behide a worker's body.

Although downflow booths have been used for control of airborne particles in the workplace, very few studies have addressed the need for assessing the control performance of conventional downflow booths,[3,5,7] compared with the research done for other controlled environments such as hospital operating rooms and cleanrooms. In this study, we designed and built a mobile downflow booth with adjustable air changes per hour or air change rates (ACHs) and work areas. Comprehensive laboratory tests were conducted by dry powder transfer between two cylindrical containers under different booth operating conditions to (1) investigate the control performance of the mobile downflow booth, and (2) evaluate worker exposure to airborne particles released from the task. Our study results provide optimization knowledge to users for the operation of downflow booths to remove air particles from their manufacturing processes.

Materials and methods

Mobile downflow booth

For our study purposes, the test downflow booth (Figure 2a) was designed to be customizable regarding ACHs and work area size. The flowrates of all ceiling fans and exhaust blowers are adjustable with variable frequency drives to keep the downflow booth running at a unidirectional supply of up to 0.61 m/s (or 120 ft/min, fpm) and at 110% of overall exhaust flow rate. The downflow booth was constructed by assembling modular frames so that it can be enlarged or downsized easily. The structure of the booth is aluminum covered with Velcro-attached vinyl to contain airflow. The height (244 cm or 8 ft from the ceiling diffusers to the ground) and width (307 cm or 10 ft) of the downflow booth depth are fixed, while the depth can be changed to short length (135 cm or 53 in measured from the air returns to the booth entrance), standard length (202 cm or 79.5 in), and extended length (270 cm or 106 in). The dimension

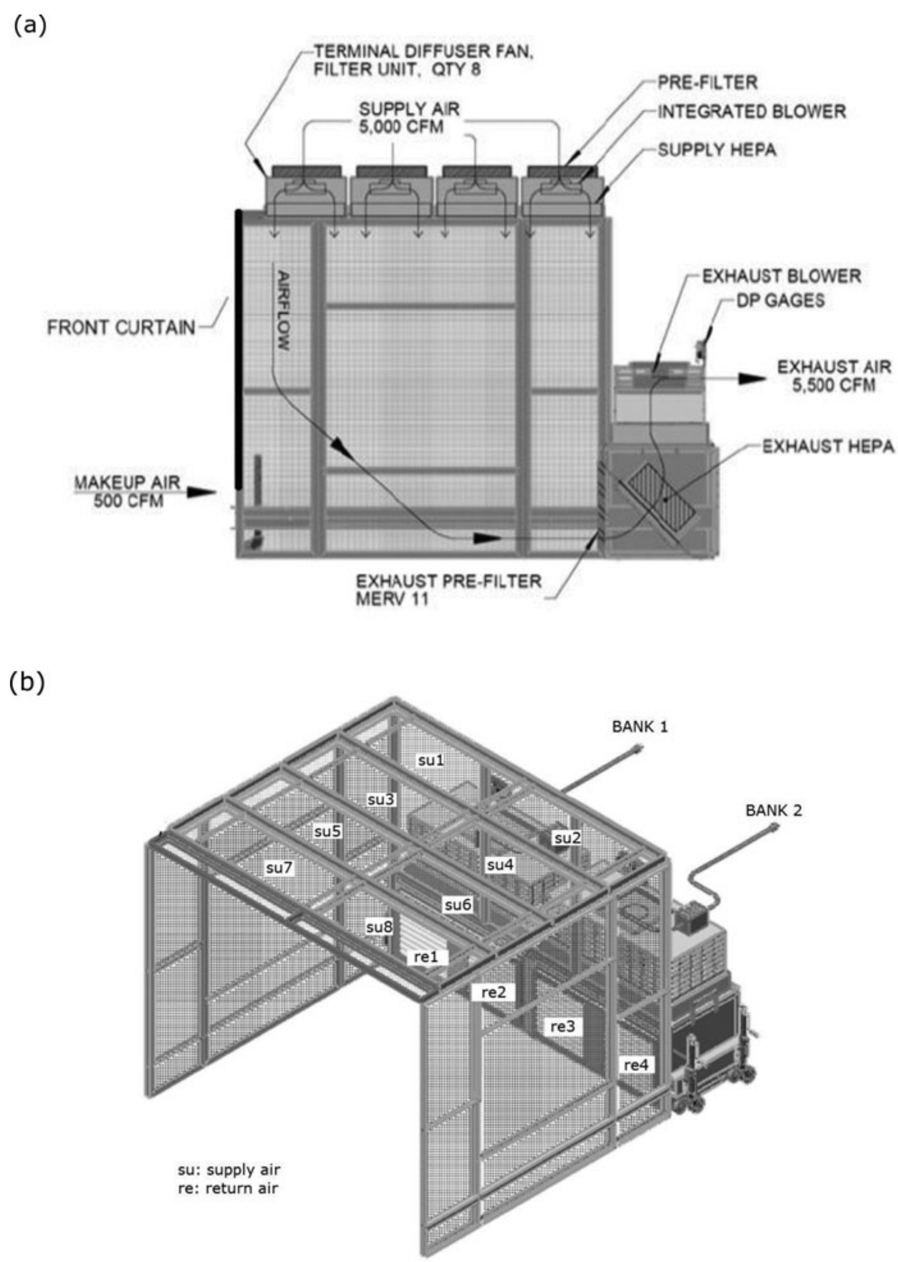


Figure 2. Design of mobile downflow booth: (a) side view and (b) top view.

Table 1. Downflow booth dimensions and locations of performing powder transfer for this study.

DFB size	Dimensions in width × height × depth, cm (or ft)	Space volume V_{DFB}, L (or ft^3)	d1 Powder transfer near air returns in Figure 3, cm (or in)	d2 Powder transfer far away from air returns in Figure 3, cm (or in)
Short	307 × 244 × 135 (10 × 8 × 4.4)	10,090 (352)	69 (27)	86 (34)
Regular	307 × 244 × 202 (10 × 8 × 6.6)	15,135 (528)	69 (27)	137 (54)
Extended	307 × 244 × 270 (10 × 8 × 8.8)	20,180 (704)	69 (27)	183 (72)

information of the test downflow booth under different arrangements is summarized in Table 1.

Overhead flow is provided by supply fans in the ceiling with a standard size of 61 × 122 cm (2 × 4 ft). Every fan is equipped with one pre-filter at the top inlet, one HEPA filter inside the plenum, and a diffuser grill at the bottom air outlet. There are eight ceiling supply fans (named su1−8 as shown in Figure 2b) required for operating the downflow booth at extended size; six (su1−6) for standard size; and four (su1−4) for short size. Two exhaust air plenum assemblies (called Banks 1 and 2) behind the rear wall were used to remove contaminated air generated from the performance of tasks or manufacturing processes. Each stack exhaust assembly consists of two pre-filters rated MERV 11 and two HEPA filters in the bottom plenum, and a direct drive motor coupled to a blower in the top plenum. The top plenums have exhaust ducts and slide gates to allow users to exhaust filtered air to the outdoors or back into the room. As shown in Figure 2b, there are four air returns (re1−4), two each for the two exhaust banks.

Unlike traditional downflow booths recirculating 90% return air, the test downflow booth does not recirculate any filtered air. Air supply to the booth is made up of clean air through the ceiling fans and fresh air from the front of the booth. Note that the entrance of the test booth is covered by removable vinyl curtains, 179 cm (70.5 in) long that make a nearly 65 cm (25.5 in) high opening above the floor. The vinyl curtains can be removed completely to comply with requirements from various processes or tasks. To operate the test booth at a slightly lower pressure than its surroundings, the exhaust blowers need to remove 10% more air than the overall airflow from the ceiling fans. Therefore, the 10% fresh makeup air is drawn into the front of the booth from the room.

Test protocol

There are a few standards specifying test methods for characterizing the performance of controlled environments.[4,8–10] The guidebook published by the International Society for Pharmaceutical Engineering (ISPE) provides a standard methodology for assessing the containment efficiency of equipment including downflow booths used in the pharmaceutical industry.[4] The guide provides general recommendations about surrogate test materials, test activities/processes, test runs/cycles, sampling locations, data collection, and analysis. For our study purposes, we created a comprehensive test plan to evaluate the performance of the downflow booth. This was done by calculating the removal of airborne particles generated by powder transfer activities inside the downflow booth.

Test procedures and experimental factors

Lactose is one of the surrogate test materials recommended by ISPE.[4] There are no exposure limits established for lactose by Occupational Safety and Health Administration (OSHA) and American Conference of Governmental Industrial Hygienists (ACGIH), but this test material can be traeated as a nuisance dust which is the same as the Particulateds Not Otherwise Regulated limit in OSHA 1910.1000 Table Z-3. Therefore, the permissible exposure levels (PELs) for lactose are 5 mg/m^3 TWA for respirable fraction and 15 mg/m^3 TWA for total dust. Due to its low cost and toxicity, lactose (Phamatose 450M, DFE Pharma, Germany) was chosen as the test material in this study. The mean particle size of test lactose is less than 45 µm, which should provide a consistent particle size distribution and shape. The simulated processes or tasks must continuously and consistently release airborne particles into the work area to allow for the evaluation of the performance of the downflow booth.

In this study, worker activity was simulated by manual substance transfer between two barrels of lactose powder. Airborne particles were generated by an operator manually transferring lactose with a stainless steel scoop between two side-by-side open barrels (hereafter called Containers A and B) that hold a total of 25 kilograms lactose. Containers A and B had identical dimensions, the base was 33 × 38 cm (13 × 15 in), the height was 63.5 cm (25 in), and the diameter of the open top was 26 cm (10 in). As shown in Figure 3, the operator continuously transferred lactose from Container B to A during each 3-minute test cycle. The operator repeated the 3-minute test cycle 10 times (or 10 test runs) under one test condition to collect enough data for statistical analysis. Between each test cycle, the operator had a 2-min break to allow the downflow booth to remove all airborne particles and for

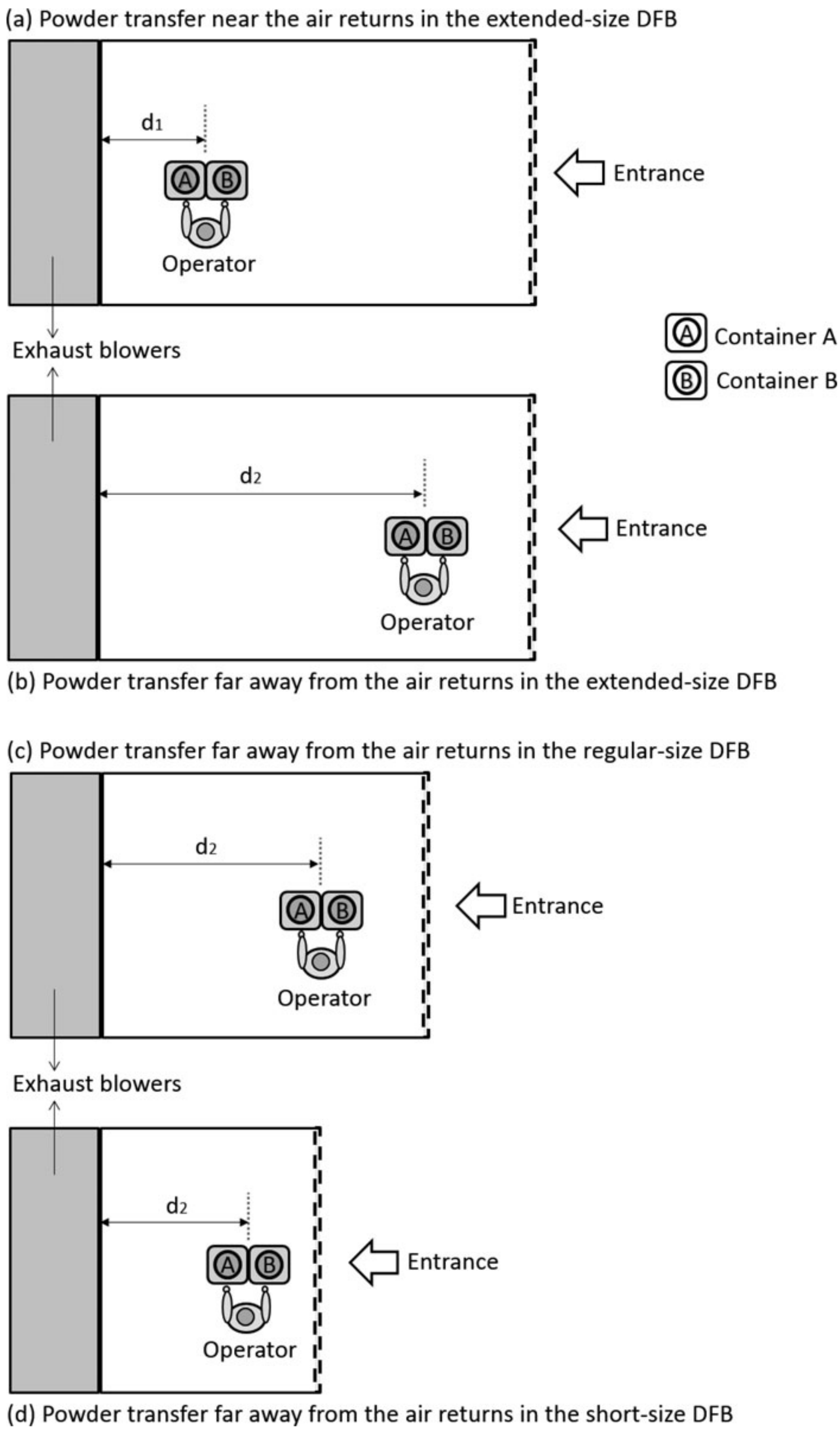


Figure 3. Powder transfer locations on top views of the downflow booths. The location to perform powder transfer near the air returns, shown in Figure 3a, was kept at d_1 (i.e., 69 cm from the air returns) for different booth sizes.

the operator to switch containers for next test cycle. This test procedure required the operator to perform at least 800 transfers for each test condition. The work area was cleaned after completing each test condition to ensure that data obtained from each test condition was independent. The large sample size allowed the finding of statistically significant evidence of a difference between different test conditions. During the tests, the operator wore all necessary personal protective equipment including a respirator, PVC gloves, earplugs, and disposable protective clothes.

Supply air velocity from the ceiling fans of the downflow booth plays a critical role in reducing occupational exposure to workers. A downflow booth typically provides unidirectional filtered airflow of between 0.46 and 0.51 m/s (90 and 100 fpm) measured from 7.6 cm (3 in) from the diffuser screen. To investigate the effect of supply airflow velocity on reducing exposure levels, two different supply velocities, 0.41 m/s (80 fpm) and 0.51 m/s (100 fpm), were tested in this study. Under normal operations, the safe working zone of the test downflow booth is nearly 2/3 (66%) of the booth depth as shown in Figure 1. Tasks or activities should be taken place toward the booth exhaust, but workers might perform tasks far away from the booth exhaust due to limited work space in practice. To understand the extent of the safe working zone, the powder transfer was performed at two different locations: near the air returns (69 cm or 27 in from the rear wall) and far away from the air returns (locations will vary based on the booth size tested, as shown in Table 1 and Figure 3). Air curtains are often installed on the entrance of a downflow booth to provide higher containment efficiency to keep particles from escaping into the work environment.The use of curtains reduces airflow disturbance and is expected to slightly increase the safe working zone. The use of vinyl curtains on the downflow booth was examined here to understand if they actually contributed to additional protection for workers.

Therefore, there were four control factors evaluated in this study: size of the downflow booth (short, regular, or extended), supply airflow velocity (high at 0.51 m/s or 100 fpm and low at 0.41 m/s or 80 fpm), powder transfer locations (near or far from the air returns or exhausts), and vinyl curtains (use or not use). Table 2 lists all the test conditions conducted in this study. Because all the tests conditions are independent, we completed the tests in the order shown in Table 2 for convenience to simplify resizing the downflow booth and adjusting supply air velocity.

Sampling methods

A rotating vane connected to a micromanometer (Model EB730, TSI Inc., Shoreview, MN) was placed 7.6 cm (3 in) from the right-half and left-half sides of the diffuser screen to obtain average supply air velocity. Every supply fan was adjusted to reach the desired supply air velocity within 5% deviation. Next, a 2 × 4 Balometer Capture Hood (Model EBT731, TSI Inc., Shoreview, MN) was used to measure volumetric flow rates of supply fans to obtain the overall supply flow rate (Q_s). To achieve the desired overall exhaust flow rate (110% of Q_s, or Q_e), the exhaust blowers were adjusted based on the measurements from a 2 × 2 Balometer Capture Hood on each air return. The same micromanometer was used for all the velocity and flow rate measurements to ensure data reliability. The air change rate (ACH) of the downflow booth for every test condition can be calculated as

$$\mathrm{ACH} = \frac{60Q_e}{V_{DFB}}, \tag{1}$$

where Q_e is overall exhaust volumetric flow rate in liters per minute (Lpm), and V_{DFB} is the space volume of the downflow booth in liters (L) as shown in Table 1.

Table 2. Test conditions for evaluating control performance of downflow booths.

	Factors			
DFB operating condition	DFB Size	Supply air velocity m/s (fpm)	Powder transfer Location measured from exhausts	Curtains
1	Regular	0.41 (80)	Near	Yes (use)
2	Regular	0.41 (80)	Near	No (not use)
3	Regular	0.51 (100)	Near	Yes
4	Regular	0.51 (100)	Near	No
5	Short	0.51 (100)	Near	Yes
6	Short	0.51 (100)	Near	No
7	Short	0.41 (80)	Near	No
8	Short	0.41 (80)	Near	Yes
9	Extended	0.51 (100)	Near	No
10	Extended	0.51 (100)	Far	No
11	Extended	0.51 (100)	Far	Yes
12	Extended	0.51 (100)	Near	Yes
13	Extended	0.41 (80)	Near	Yes
14	Extended	0.41 (80)	Near	No
15	Extended	0.51 (80)	Far	Yes
16	Extended	0.41 (80)	Far	No
17	Regular	0.41 (80)	Far	Yes
18	Regular	0.41 (80)	Far	No
19	Regular	0.51 (100)	Far	Yes
20	Regular	0.51 (100)	Far	No
21	Short	0.51 (100)	Far	Yes
22	Short	0.51 (100)	Far	No
23	Short	0.41 (80)	Far	Yes
24	Short	0.41 (80)	Far	No

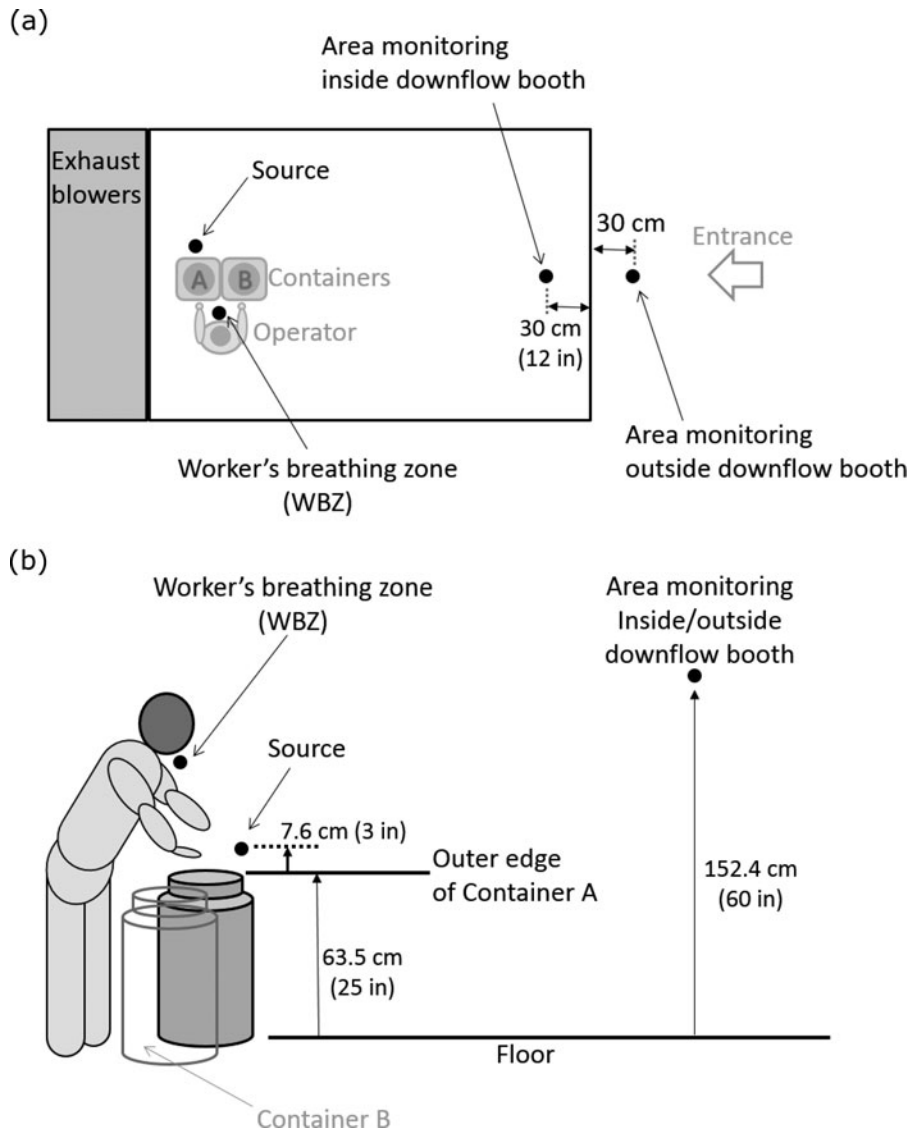


Figure 4. (a) Sampling locations shown on top view of the downflow booth, and (b) details of sampling locations of source and WBZ.

For every test condition, airborne particle concentrations were measured and logged in real-time by direct-reading instruments located at several sampling locations; these include the source of contamination, WBZ, and inside/outside the downflow booth (shown in Figure 4a). As shown in Figure 4b, source particle concentrations were measured 7.6 cm (3 in) above the outer edge of Container A, or 71 cm (28 in) above the floor. Sampling probes were located on the right collar of the protective suit worn by the operator to collect aerosol concentrations as close as possible to the WBZ. Due to body movement during manual powder transfer, the sampling location of WBZ changed between 40.6 cm (16 in) above the opening of Container B when standing and 20.3 cm (8 in) above when scooping. Aerosol sampling inside and outside the downflow booth was measured 30 cm (12 in) inward and outward from the entrance of the booth at a height of 152.4 cm (60 in) from the floor.

Direct-reading instruments used for this study to measure airborne particle concentrations included Aerodynamic Particle Sizers (APS, Model 3321, TSI Inc.), Optical Particle Sizers (OPS, Model 3330, TSI Inc.), DustTrak Aerosol Monitors (Model 8533, TSI Inc.), and SidePak Personal Aerosol Monitors (Model AM510, TSI Inc.). Each instrument provided real time measurements to help identify particle emissions from the task of powder transfer. The APS determines number size distributions from 0.5–20 µm at a total sampling flowrate of 5.0 Lpm with a light-scattering technique. It has high size resolution up to 52 channels but requires a data collection system such as a computer for data logging. The OPS can detect particles ranging from 0.3–10 µm at a sampling flowrate of 1.0 Lpm in up to 16 user-adjustable size channels. The DustTrak measures airborne particles from 0.1–15 µm at a sample flowrate of 3.0 Lpm. It can simultaneously measure size-segregated mass fraction concentrations corresponding to PM1, PM2.5, Respirable, PM10, and Total PM size fractions. The SidePak aerosol monitor provides total mass concentration covering particle sizes from 0.1–10 µm at a sampling flowrate of 1.7 Lpm. For these tests, the SidePaks were always used with 10-mm Nylon Dorr-Oliver Cyclones to obtain respirable fractions (cut off at 4 µm). In summary, three identical instrument sets of OPS/DustTrak/SidePak sampled particles at source, WBZ, and inside the booth, while only a SidePak monitored the concentrations outside the booth during the tests. There were no other activities or experiments conducted in the laboratory during testing, ensuring that the only contaminant detected was the test lactose.

Data analysis

To compare the particle removal efficiency of the downflow booth under different test conditions, we proposed a performance index called particle reduction ratio (PRR), calculated as

$$\mathrm{PRR} = 0.5\,\mathrm{ACH} \times \frac{C_S - C_{WBZ}}{C_S}, \qquad (2)$$

where ACH can be obtained from Equation (1), and C_S and C_{WBZ} are the overall average particle concentrations at the source and WBZ, respectively. The constant of 0.5 is used because the total transfer time was one half hour.

To understand the influence of variable factors on the control performance of downflow booths, the average particle number or mass concentrations during each test cycle of all test conditions were calculated for statistical analysis. The Analysis of Variance (ANOVA) model[11] was used followed by Tukey Multiple comparison procedures to test the statistical differences in these performance indices among four control factors mentioned above and their interactions.[12] The logarithm-transformed particle reduction ratios were used to meet the normality assumption for the ANOVA analysis.[13]

Results and discussion

Flow measurement

Table 3 summarizes the airflow measurement data obtained by Balometer Capture Hoods for the three different sizes of the test booth and computed ACHs based on Equation (1). When using the same supply air velocity, the ACHs of the different downflow booth sizes are comparable. For this study, 336 ACHs on average can be achieved by running the test booths at 0.41 m/s (80 fpm) supply air velocity, and 401 ACHs on average while operating the booths at 0.51 m/s (100 fpm). Room ACHs can be increased by 20% on average if the downflow booth was operated at the higher supply air velocity.

Table 3. Flow measurement results of downflow booths operated at different supply air velocities.

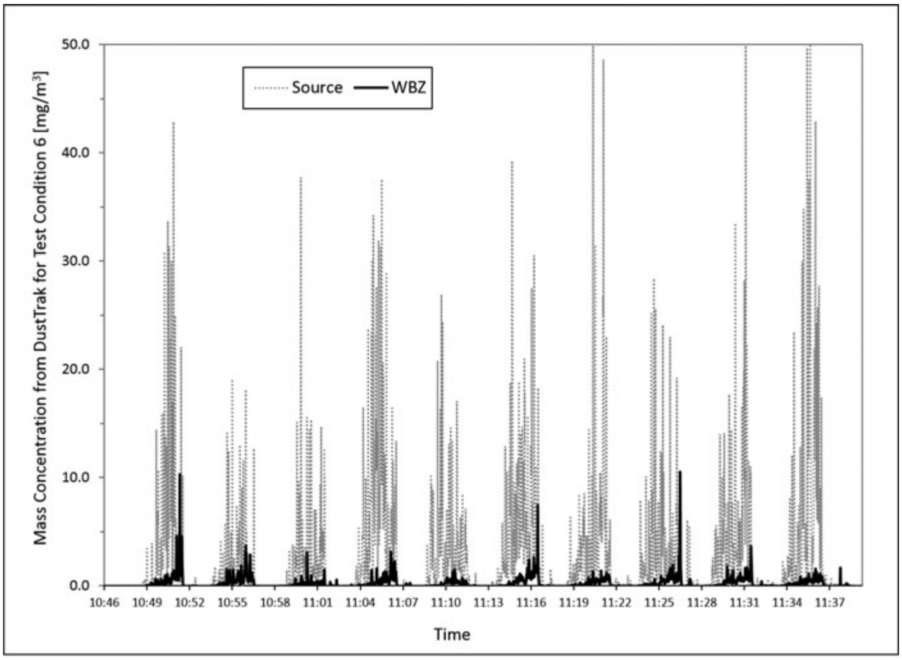
Downflow booth Size	Nominal supply air velocity, m/s (fpm)	Q_s Average total supply flowrate (Lpm)	Q_e Average total exhaust flowrate (Lpm)	Average ACH
Short	0.41 (80)	51,452	56,378	335
	0.51 (100)	59,918	66,488	395
Regular	0.41 (80)	73,850	83,478	331
	0.51 (100)	90,387	100,779	400
Extended	0.41 (80)	104,121	115,391	343
	0.51 (100)	124,764	137,054	408

Measurements during powder transfer

During each test, the particle concentrations inside and outside the test booth were stable and stayed near zero. These results indicated that the downflow booth provides excellent containment, because half of the powder transfer tests were performed far away from the booth exhausts (near the entrance of the test booth). Airborne particles could only be detected at the source and WBZ during powder transfers, and the concentrations decreased to zero during the 2-min breaks. The measurement data at the source and WBZ showed a consistent tendency and comparable responses to worker activities among the different instruments. Figure 5 shows two real-time measurement data from a DustTrak monitor for Test 6 and an OPS for Test 15 as examples to demonstate excellent performance of particle reduction by the downflow booth.

Because the APSs are bulky and require computers for data logging, we only used them to accompany the OPSs to sample number size distributions at the source and WBZ for the first eight test conditions (see Table 2). We found the APS data comparable to the OPS results in the total number concentrations. For the remaining tests, the number size distributions were measured by the OPSs that had been programmed to match the APS size channels. Some data from the SidePaks at the source and WBZ were lost due to incorrect data logging settings, but all data collected from the DustTraks and OPSs were recorded allowing computation of PRRs for performance comparison.

Table 4 summarizes the overall average concentrations at source and WBZ during powder transfers and computed PRRs for all the tests. The same information was depicted in Figure 6a for DustTrak data and Figure 6b for OPS data. Among 24 runs, Tests 21–24 showed negative results for PRRs (i.e., concentrations at the WBZ were higher than those at source). To understand why the downflow booths failed to protect the operator under



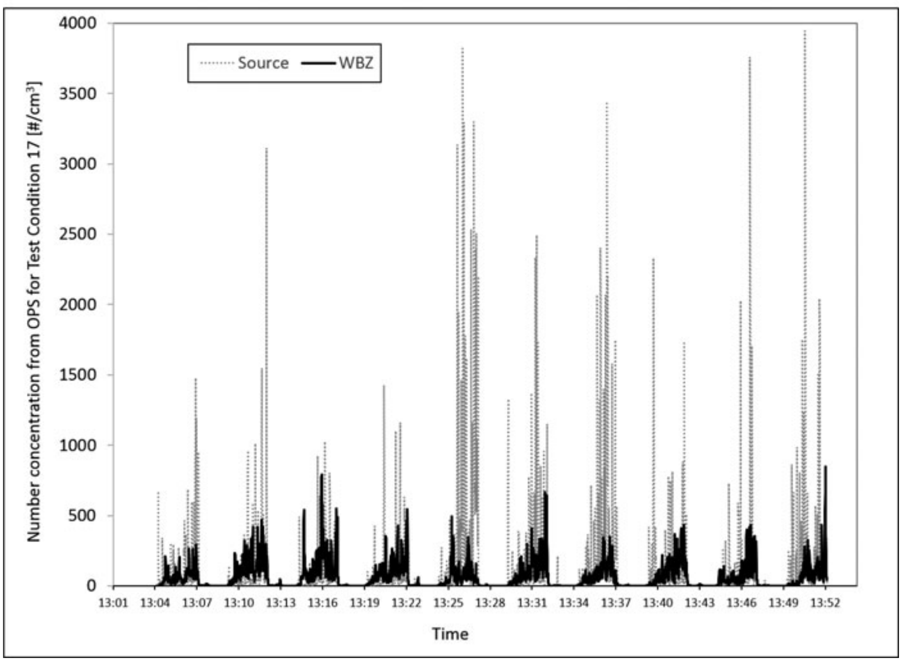


Figure 5. Real-time airborne particle measument data at source and WBZ monitored by (a) DustTrak for Test Condition 6 and (b) OPS for Test Condition 17.

these test conditions, it was necessary to inspect the real-time data collected from the instruments: Figure 7a, DustTrak data for Test 22 and Figure 7b, OPS data for Test 23. The real-time data from Figure 7 indicate that concentrations at the source were constantly generated by work activity, but the airborne particles reached the WBZ and increased continuously until the end of powder transfers. For Tests 21–24, we also observed that the rising plume of lactose generated by powder transfer was not removed by airflows as quickly as other tests. Changing supply air velocity and using air curtains did not provide any improvement in case of powder transfer far away from the air returns in short-depth downflow booths (Tests 21–24). They clearly indicated that short-depth downflow booths failed to remove particles when the powder transfer was performed close to the edge of safe working zone due to their limited safety workspace. As demonstrated in Figure 5, however, Tests 1–20 showed positive results. The airborne particles were removed at the WBZ to keep concentrations relatively lower than those generated at the source. Therefore, only the measurement data obtained from Tests 1–20 were used for

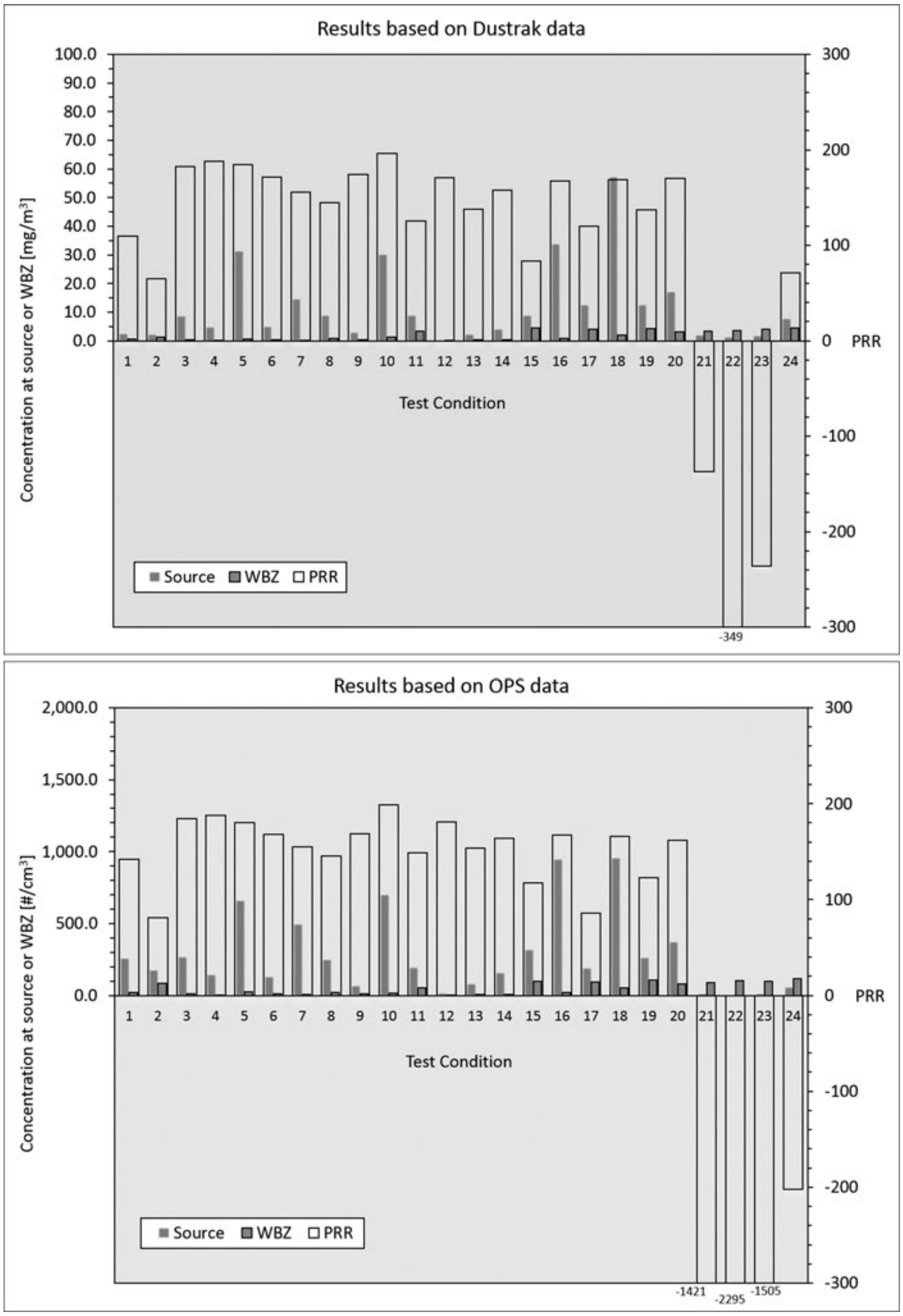


Figure 6. Summary of test results based on (a) DustTrak data and (b) OPS data.

statistical analysis to examine the effect of experimental factors on control performance.

Statistical analysis

The results of the statistical analysis are summarized in Table 5. The geometric means and standard deviations of PRRs from various test conditions (Tests 1–20) were used to indicate the central tendency of the data set. According to an ANOVA F-test, statistically significant differences in booth size, supply air velocity, and the use of curtains were found from both measurement instruments. The detailed discussions follow.

(1) Size of downflow booth: ANOVA analysis indicated that conducting powder transfer in short and extended downflow booths did not make any significant difference in the proposed performance indices (PRRs), but performance of the regular downflow booth was worse than the other two cases.
(2) Supply air velocity: Tukey multiple comparisons indicated that PRRs are higher when the test booths were operated at 0.51 m/s (100 fpm) of supply air velocity than at 0.41 m/s (80 fpm). This conclusion was expected because

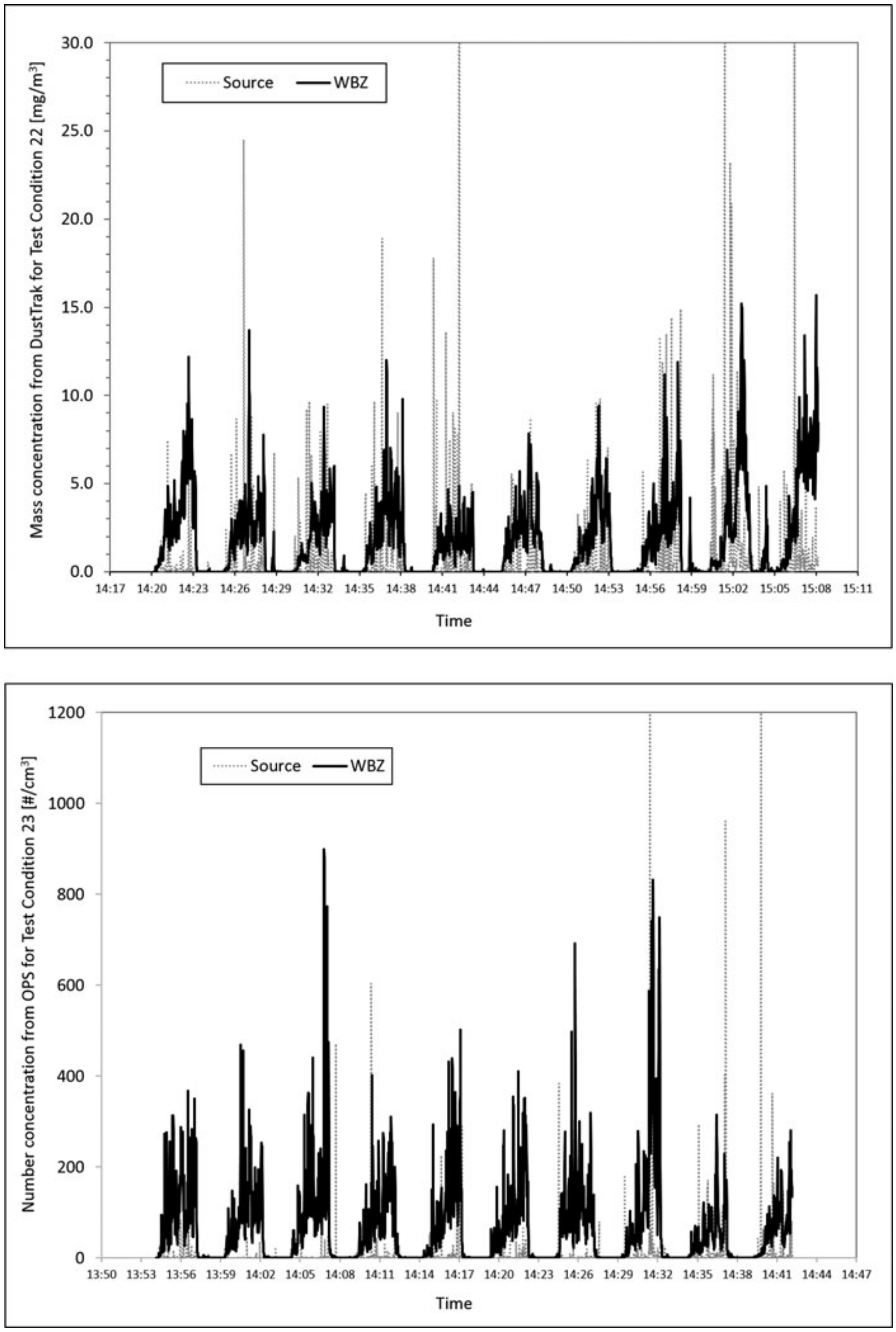


Figure 7. Real-time measurment data showing that the downflow booths failed to control airborne particles: (a) Test Condition 22 monitored by DustTrak and (b) Test Condition 23 monitored by OPS.

of higher room ACHs provided by supply air at 0.51 m/s (100 fpm), which leads to improved airborne particle reduction.

(3) Location for powder transfer: All the locations to perform powder transfer either near or far away from the air returns were within the safe working zone of the test booths. Tukey multiple comparisons indicated that powder transfer at either location did not have any significant difference based on DustTrak data, but OPS data showed powder transfer near the air returns obtained better performance. In summary, airborne particles inside the safe working zone can be effectively removed by the downflow booth. When powder transfer was performed far away from the air returns, the short downflow booth failed to protect the worker (as shown in Tests 21—24), but the larger size downflow booths still functioned well. The underperformance of the short downflow booth could be attributed to its smaller space between the edge of safe working zone and the booth entrance. Compared with other

Table 4. Test results from performing powder transfer inside downflow booths.

	DustTrak			OPS		
Test Condition	Source [mg/m^3]	WBZ [mg/m^3]	PRR	Source [#/cm^3]	WBZ [m#/m^3]	PRR
1	2.31	0.69	109	257.75	22.88	142
2	2.23	1.31	65	176.27	84.72	81
3	8.50	0.47	182	268.46	12.13	184
4	4.67	0.11	188	145.70	4.01	188
5	31.32	0.52	184	659.02	26.62	180
6	4.85	0.42	171	131.60	13.53	168
7	14.45	0.18	155	494.81	7.73	155
8	8.85	0.72	145	249.89	18.99	146
9	2.83	0.42	174	67.67	11.78	168
10	30.23	1.20	196	699.89	17.01	199
11	8.87	3.41	126	192.81	51.95	149
12	0.37	0.06	171	14.23	1.59	181
13	2.09	0.41	138	80.78	8.35	154
14	4.05	0.32	158	157.43	7.15	164
15	8.81	4.52	83	316.20	100.20	117
16	33.85	0.87	167	945.38	21.58	168
17	12.59	3.97	120	187.36	95.23	86
18	57.09	2.01	169	955.03	50.72	166
19	12.49	4.21	137	262.91	106.78	123
20	17.16	3.00	170	373.70	80.85	162
21	1.95	3.23	−137*	11.45	89.65	−1421*
22	1.31	3.49	−346*	8.60	103.47	−2295*
23	1.73	4.01	−236*	10.41	98.42	−1505*
24	7.59	4.54	71	55.54	118.58	−202*

*Downflow booths operated under the specific conditions failed to remove particles.

tests, Tests 21—24 were conducted at a location closer to the booth entrance, but not provided enough space to form desired air flows to remove contaminants.

(4) Use of curtains: Use of curtains on downflow booths is commonly believed to enhance their control performance. However, the statistical analysis of our test data clearly indicated that downflow booths without installation of curtains have better performance. The curtains were installed on the test booths to make a nearly 65 cm (25.5 in) high opening above the floor to draw 10% makeup air from the room to the booth. The curtain opening is about the same height as the cylindrical containers (63.5 cm or 25 in). Before reaching the safe working zone, makeup air from the curtain opening could create eddies and recirculation zones. Unwanted airflow disturbance above the containers could transport contaminants into WBZ, especially for the cases of powder transfer far away from the air returns (i.e., close to the booth entrance).

Table 5. Results from statistical analysis for comparison of control performance of downflow booths.

				PRR	
Measurement instrument	Experimental factors	Levels	Sample size	Geometric mean	Geometric standard deviation
DustTrak	Booth size*	Short	40	161.58	1.115
		Regular	78	117.77	2.073
		Extended	76	140.92	1.501
	Supply air velocity*, m/s (fpm)	0.41 (80)	95	112.66	1.921
		0.51 (100)	99	160.27	1.389
	Location for powder transfer	Near	117	139.93	1.739
		Far	77	127.52	1.685
	Use of curtains*	Yes	97	119.96	1.755
		No	97	151.61	1.642
OPS	Booth size*	Short	40	159.66	1.109
		Regular	76	124.11	1.90
		Extended	79	150.00	1.387
	Supply air velocity*, m/s (fpm)	0.41 (80)	95	125.41	1.653
		0.51 (100)	100	157.86	1.481
	Location for powder transfer*	Near	118	152.65	1.347
		Far	77	125.11	1.863
	Use of curtains*	Yes	97	130.23	1.733
		No	98	152.79	1.408

Note: Experimental factors showing statistically significant difference were marked with asterisks.

Conclusions

With a proposed performance index (PRR), a rigorous study has been conducted to evaluate the control performance of downflow booths used for removing airborne particles generated from powder transfer of lactose between two containers. During all the tests, the particle concentrations inside and outside the test booth were stable and were maintained at nearly zero for all the tests. Once powder transfer was stopped, particles at the source and WBZ positions were removed effectively; the concentrations were quickly reduced to near zero counts. Our experimental data demonstrate that downflow booths are excellent engineering control measures to contain and mitigate airborne particles in the workplace.

Normally, workers can be protected from exposure to airborne particles when they perform tasks or activities within the safe working zone of downflow booths. An exception occurred when particles were generated close to the edge of the safe working zone of a limited-space downflow booth (i.e., short-depth booth in our study). In that case, the downflow booth cannot remove source particles effectively, but particle concentrations increased at WBZ continuously. Therefore, a downflow booth should not be used with performing tasks outside the edge of the safe working zone, because it cannot provide adequate protection to workers under the circumstances. Sufficient supply air velocity is a major factor that enables downflow booths to be good engineering controls in the workplace. As expected, our test data have shown that better control performance can be obtained with supply air velocity of 0.51 m/s (100 fpm) than with 0.41 m/s (80 fpm) that is lower than typical velocities of 0.46−0.56 m/s (90–110 fpm). Our study also found that use of curtains for downflow booths did not improve their control performance. In contrast, downflow booths without curtains installed on the entrance reduced particles more effectively.

In practice, downflow booths may be used for various tasks in different industries, and their control performance is not always effective for protecting workers if operated inappropriately. The use of secondary control systems may allow for better containment and control while the downflow booth provides the primary containment of generated dusts. However, the use of additional controls inside the downflow booth could also cause unacceptable outcomes if the controls adversely affect the critical airflow patterns developed by the booth. The main factor affecting the performance of the mobile downflow booth is the system airflow characteristics. Future work will be to use airflow visualization tools to understand critical airflow patterns maintained inside the booth during different occupancy states. This will also aid in identifying eddies and recirculation zones that could transport airborne particles into WBZ when they perform tasks inside the downflow booth.

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Disclaimer

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References

[1] **ACGIH:** *Industrial Ventilation: A Manual of Recommended Practice for Design* (*28th Edition*). Cincinnati, OH: American Conference of Governmental Industrial Hygienists, 2013.

[2] **WHO:** *Hazard Prevention and Control in the Work Environment: Airborne Dust*. World Health Organization (ed.). Geneva, Switzerland, 1999.

[3] **Floura, H., and J. Kremer:** Performance verification of a downflow booth via surrogate testing. *Pharma Eng. 28*(6):9 (2008).

[4] **ISPE:** *ISPE Good Practice Guide: Assessing The Particulate Containment Performance of Pharmaceutical Equipment*. Tampa, FL: International Society for Pharmaceutical Engineering, Inc., 2012.

[5] **Lin, X.Q., and Y. Nestiti:** "Performance Verification of ESCO Pharmacon Downflow Booth via Surrogate Air Monitoring Exposure to Lactose during Material Transfers Involving 25 kg of Active Pharmaceutical Ingredient". [Online] Available at http://www.escoglobal.com/resources/pdf/DFB_surrogate_powder_test.pdf (2009).

[6] **Walker Barrier Systems:** "Case Study: Dust in Air Testing in a Downflow Booth". [Online] Available at http://www.pharmaceuticalonline.com/doc.mvc/Dust-In-Air-Testing-In-A-Downflow-Booth-0001 (2008).

[7] **Heitbrink, W.A., L.-M. Lo, and K.H. Dunn:** Exposure controls for nanomaterials at three manufacturing sites. *J. Occup. Environ. Hyg. 12*(1):16–28 (2015).
[8] **IEST:** *IEST-RP-CC006.3 Testing Cleanrooms*. Arlington Heights, IL: Institute of Environmental Sciences and Technology, 2004.
[9] **ISO:** *ISO 14644-3:2005 Cleanrooms and Associated Controlled Environments – Part 3: Test Methods*. Switzerland: International Organization for Standardization, 2005.
[10] **CETA:** *CETA CAG-002-2006: Compounding Isolator Testing Guide*. Raleigh, NC: Controlled Environment Testing Association, 2008.
[11] **SAS:** Software Version 9.3 (TS1 M2). Cary, NC, 2012.
[12] **Hochberg, Y., and A.C. Tamhane:** *Multiple Comparison Procedures*. New York, NY: John Wiley & Sons, Inc., 1987.
[13] **Searle, S.R.:** *Linear Models*. New York, NY: John Wiley & Sons, Inc., 1971.