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EVALUATION OF LEAKAGE FROM FUME HOODS USING TRACER GAS, TRACER NANOPARTICLES AND NANOPOWDER HANDLING TEST METHODOLOGIES

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Abstract

The most commonly reported control used to minimize workplace exposures to nanomaterials is the chemical fume hood. Studies have shown, however, that significant releases of nanoparticles can occur when materials are handled inside fume hoods. This study evaluated the performance of a new commercially available nano fume hood using three different test protocols. Tracer gas, tracer nanoparticle, and nanopowder handling protocols were used to evaluate the hood. A static test procedure using tracer gas (sulfur hexafluoride) and nanoparticles as well as an active test using an operator handling nanoalumina were conducted. A commercially available particle generator was used to produce sodium chloride tracer nanoparticles. Containment effectiveness was evaluated by sampling both in the breathing zone (BZ) of a mannequin and operator as well as across the hood opening. These containment tests were conducted across a range of hood face velocities (60, 80, and 100 feet/minute) and with the room ventilation system turned off and on. For the tracer gas and tracer nanoparticle tests, leakage was much more prominent on the left side of the hood (closest to the room supply air diffuser) although some leakage was noted on the right side and in the BZ sample locations. During the tracer gas and tracer nanoparticle tests, leakage was primarily noted when the room air conditioner was on for both the low and medium hood exhaust air flows. When the room air conditioner was turned off, the static tracer gas tests showed good containment across most test conditions. The tracer gas and nanoparticle test results were well correlated showing hood leakage under the same conditions and at the same sample locations. The impact of a room air conditioner was demonstrated with containment being adversely impacted during the use of room air ventilation. The tracer nanoparticle approach is a simple method requiring minimal setup and instrumentation. However, the method requires the reduction in background concentrations to allow for increased sensitivity.

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Keywords

nanoparticle; fume hood; containment; tracer gas

INTRODUCTION

Occupational health risks associated with manufacturing and the use of nanomaterials are not yet clearly understood. However, initial toxicological data indicate that there is reason for caution. Pulmonary inflammation has been observed in animals exposed to titanium dioxide (TiO_2) and carbon.[1-3] Other studies have shown that nanoparticles can translocate to the circulatory system and to the brain and cause oxidative stress.[4, 5] Perhaps the most troubling finding is that carbon nanotubes can elicit asbestos-like responses in mice.[6, 7] In light of these results, it is important for producers and users of engineered nanomaterials to reduce employee exposure and manage risks appropriately.

A survey was conducted of producers and users of engineered carbonaceous nanomaterials (ECNs) in the U.S. at a research and development or pilot scale plant with plans to scale up within 5 years.[8] All participating companies reported using some sort of engineering control to reduce worker exposure to ECN. The most commonly reported control used to minimize workplace exposures to ECN was the chemical fume hood. Recent research has shown that the fume hood may allow releases of nanomaterials during their handling and manipulation.**[9]** This research evaluated exposures related to the handling (i.e., scooping and pouring) of powder nanoalumina and nanosilver in a constant air volume (CAV) hood, a bypass hood, and a variable air volume (VAV) hood. The study showed that the conventional fume hood in which face velocity varies inversely with sash height allowed the release of significant amounts of nanoparticles during pouring and transferring activities involving nanoalumina. New lower flow hoods adapted from pharmaceutical powder handling enclosures are being marketed and used for the manipulation of nanomaterials. The use of lower flows may reduce the impact of turbulence and the body wake on the potential for fume hood leakage. However, there is little information on their performance in the scientific literature.

A common method used to evaluate performance of fume hoods is the quantitative tracer gas test. These tests are sometimes conducted with a mannequin in front of the hood to simulate the effect of the user on the air patterns surrounding the face of the hood. For these tests, a tracer gas (typically sulfur hexafluoride, SF_6) is released inside the hood using a dispersion device. The performance of the hood is evaluated by measuring the tracer gas concentration at the breathing zone (BZ) of the mannequin or at the hood opening. Tseng et al. evaluated the results of British, European and American protocols for tracer gas fume hood testing using a traditional laboratory fume hood. This testing showed that airflow patterns and the performance of the hood are integrally related.[10] The choice of source position, hood design and presence of a mannequin are important to a careful evaluation of the fume hood. The American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) standard evaluates fume hood performance based on the traditional industrial hygiene precept of evaluating operator breathing zone exposure.[11] Tseng et al.

found, however, that this method failed to detect serious leakages which may not be acceptable for hazardous materials. The British standard suffered from a measurement method which averages the spatial variability and dampened the effect of local leaks by combining sample flows from all locations across the hood face.

New test methods need to be developed and evaluated. Most laboratory fume hood test protocols used today are based on utilizing SF_6. SF_6, however, has been identified as a strong greenhouse gas with a global warming potential 23,900 times greater than carbon dioxide. [12] The state of California has prohibited the sale and use of SF_6 for a broad range of applications and allowed the use for one-time testing of fume hoods "for the purpose of reducing laboratory fume hood face velocity when the hood is unattended and realizing the associated energy savings".[13] ASHRAE Technical Committee TC 9.10, Laboratory Ventilation, has recommended research to investigate potential replacement tracers critical for verification of laboratory fume hood devices.

This study evaluated the performance of a new nano fume hood across three different hood exhaust air flows using three different test protocols. For the testing, tracer gas, tracer nanoparticle and nanopowder handling protocols were used to evaluate the hood. A static test procedure using tracer gas and nanoparticles and an active test using an operator handling nanoalumina were conducted. Samplers were placed in the operator breathing zone as well as at the left and right corner of the hood to assess leakage from the hood at areas known to have high turbulence. These containment tests were conducted with the room ventilation system turned off and again with the system on. The results of the three test methods are compared across the range of test conditions.

METHODS

Description of Hood and Laboratory Space

The nano fume hood evaluated has interior dimensions of 20.3 inches (51.6 cm) (height) × 32 in (81.2 cm) (width) with an internal working depth of 30 in (76.3 cm) and a face opening of 9.5 in (24.1 cm) (height) × 32 in (81.2 cm) (width). The hood is constructed out of cast acrylic with a phenolic resin base. The enclosure includes a variety of features to reduce turbulence and improve containment performance. Molded airfoils are included at both sideposts, at the base of the hood inlet, and along the bottom of the hood sash. This enclosure was based on a pharmaceutical balance enclosure designed to protect workers during the handling of active pharmaceutical ingredients and to provide a low turbulence environment for weighing of materials on microbalances. This hood was located in a laboratory which was 10.5 feet (3.2 m) wide by 21 ft (6.7 m) deep with a ceiling height of 9.4 ft (2.9 m). A 2 ft (61 cm) × 2 ft (61 cm) ceiling-mounted supply air diffuser was located at the center of the room and slightly to the left of the hood face (Figures 1a and b).

Ventilation measurements

Airflow measurements were taken to characterize the inlet air flow profile at the face of the nano fume hood. A traverse of the hood face with a hot wire anemometer was conducted to evaluate the spatial and temporal variation in air velocities entering the hood. The air velocity measurements were collected using a model 9555 multi-function ventilation meter outfitted with a hot wire transducer (TSI, Inc. Shoreview, MN). These measurements were conducted without a mannequin in place and with the hood free of clutter and internal obstructions. The velocity profile was measured at the mid-plane of the hood face. Measurements were made in seven evenly spaced increments across the hood opening. Air velocity data were logged each second for one minute to characterize temporal variability. The temporal variations in air velocity are often referred to as the turbulence intensity. The turbulence intensity is a relative measure of the unsteadiness of the airflow and was calculated from the data to evaluate the impact of the room ventilation on variability in hood inlet airflow. The parameter is simply a coefficient of variation (or relative standard deviation) of the measurements in the time series. Traverses were conducted both with the room supply air unit "on" and "off" to assess the impact on the mean face velocity and turbulence at the hood inlet.

Hood exhaust air flows were measured using two 10-point Pitot traverses at orthogonal axes. Supply air diffuser air flow was measured using a model EBT731 Alnor air capture hood (TSI, Inc. Shoreview, MN). Diffuser face airspeed and direction were determined using the thermal anemometer and by using visual airflow indicators.

Tracer gas measurements

Tracer gas experiments were conducted to assess containment effectiveness of the nano hood. For this testing, a tracer gas source was set up inside the hood which consisted of a sintered bronze cylinder measuring approximately 0.4 in (10 mm) diameter by 0.8 in (20 mm) height (exhaust muffler, Speedaire, model 1A326). This disperser was positioned at the midpoint of the hood opening, (i.e. 16 in [406 mm] from each side, 4.7 in [120 mm] from the hood base, and 6 in [150 mm] inside the hood opening). A model GFC37 mass flow controller (Aalborg Instruments and Controls Inc., Orangeburg, NY) was used to meter a mixture of 10% SF_6/90% N2 (by volume) at a flow of 2 liters/ minute (L/min). SF_6 concentration data were collected at three sample points throughout the test, including: the left and right sides at hood face opening and at the mannequin BZ. The side samplers were located just outside the hood face, 3 in (75 mm) from the side airfoil (to the center of the sampler) and 4.7 in (120 mm) from the hood base (Figure 2a). All samples were collected simultaneously and logged every 2 seconds (s) using three MIRAN 205B XL Sapphire portable ambient air analyzers (Thermo Environmental Instruments, Franklin, MA). A baseline concentration was taken for each trial for 1 min prior to the release of tracer gas. The tracer gas dispersion was started and data were collected for 3.5 min; the first 30 s of data were removed to allow for stabilization of the mass flow controller and the following 3 min of data were used for analysis.

Nanoparticle Tracer Test

Tracer nanoparticle experiments were conducted to assess containment effectiveness of the nano hood. For this testing, a model 8026 NaCl particle generator (TSI, Inc. Shoreview, MN) was set up inside the hood. The output of this unit was characterized using a Fast Mobility Particle Sizer (FMPS, model 3091, TSI Inc., Shoreview, MN). The particle production rate was measured using a 20 liter carboy as a test chamber. The aerosol generator was started and chamber concentrations were allowed to stabilize. The generation rate was calculated based on the steady state chamber concentration and the sample flow of the FMPS. At steady state, the total nanoparticle output is a product of the chamber particle concentration multiplied by the FMPS flow. The aerosol generation rate was determined to be 2.85×10^8 particles/s with a geometric mean particle diameter of 92 nm and a geometric standard deviation of 1.9.

This disperser was positioned at the midpoint of the hood opening and 150 mm inside the hood opening for the nano hood. Samples were analyzed using a model 3007 Condensation Particle Counter (TSI, Inc., Shoreview, MN) with a size range of 10 nm to >1 micrometer (um) and a concentration range of up to 100,000 particles/cm^3. Nanoparticle concentrations were logged each second at three sample points throughout the test, including: the left and right sides at hood face opening, and at the mannequin breathing zone. The side samplers were located just outside the hood face 3 in (75 mm) from the side airfoil (to the center of the sampler) and 4.7 in (120 mm) from the hood base (Figure 2b). A baseline concentration was taken for 1 min prior to the start of each trial. The aerosol generator was started and data were collected for 4 minutes and used for analysis.

Nanopowder Handling Test

Containment effectiveness was also evaluated during routine nanopowder handling tests. Aluminum oxide (Al_2O_3) nanoparticles, also called nanoalumina, were used for this study (product no. 1020MR, Nanostructured & Amorphous Materials, Inc., Houston, TX). They have a reported density of 3,700 kilograms/cubic meter (kg/m^3) and primary particle size of 20-30 nm. Nanoalumina particles were dried overnight at a temperature of 150 °C to remove moisture before use. For each experiment, a 600 milliliter beaker loaded with approximately 50 grams of nanoalumina was used. Airborne concentrations were measured using the model 3007 Condensation Particle Counter at the same hood locations as the tracer gas and tracer nanoparticle testing (Figure 3a).

Nanopowder handling tasks were performed in the hood on the work surface 150 mm behind the sash opening (Figure 3b). Baseline particle measurements were taken for a period of 2 min before particle handling in the hood at each sample location. Particle measurements made during handling tasks were corrected for baseline to assess containment effectiveness of the hood. Particle handling methods developed by Tsai et al. were performed by manually transferring the powder between 600 ml beakers as shown in Figure 3b for a period of 3 min [9]. Following the completion of transfer, the powder was poured back into the original beaker. The transferring task was performed by using a spatula to transfer nanoparticles from one beaker to another beaker; an average of 22.1 g (SD: 2.59) of nanoalumina were transferred by spatula between beakers during each 3 min sampling period.

Hood containment tests

Hood containment testing was conducted using tracer gas, nanoparticle and nanopowder handling test methods described above across a range of test conditions. Hood exhaust air flows of 242, 348, and 445 ft^3/min (6.86, 9.86 and 12.6 m^3/min), herein referred to as LO, MED, and HI, were used to represent a range of hood face velocities. These exhaust flows correspond to average face velocities of 60, 80 and 100 ft/min (0.30, 0.41 and 0.49 m/s), respectively. The standard operating condition for the nano hood would be at the MED exhaust flow (face velocity of 80 ft/min) while a typical laboratory fume hood would generally operate at the HI exhaust flow (face velocity of 100 ft/min). In addition, all conditions were conducted with the room ventilation both “on” and “off” to assess the impact of the supply air diffuser on the containment effectiveness. Tests were repeated 3 times for each test condition with all trials randomized.

During all tests, a model PAS1000 room air cleaner (Abatement Technologies, Duluth, GA) was used to reduce the room particle concentration to a level of approximately 100-300 particles/cm^3 from ambient levels typically between 5,000-10,000 particle/cm^3. The reduction in background particles allowed for the improvement in the sensitivity of leak detection. The air cleaner ran continuously during all test conditions and time was allowed between trials for any room concentration (tracer gas or nanoparticle) to decay to background concentrations before starting the subsequent trial. In addition, a baseline concentration was established for each trial and used to assess leakage for that trial.

Average tracer gas and particle concentrations were calculated for each trial by sample location (left, right, and BZ). Concentration data were corrected for baseline values measured immediately preceding the trial at that sample location. Data were analyzed using SPSS Statistics Version 19 (IBM, Armonk, NY). The concentration data were log transformed, inspected for normality, and analyzed using two-way analysis of variance. Bonferroni multiple comparison tests were conducted to evaluate the differences in concentrations between hood exhaust flows.

RESULTS

Hood Face Velocity Testing

The face velocities of the nano hood are shown in Table I and consist of seven measurements across the face of the hood. These measurements were taken with and without the room ventilation system turned on. In addition, turbulence intensity values are provided for each sample location for both room ventilation conditions. When the room ventilation was turned on, the turbulence intensity across the hood face increased especially at the lowest face velocity condition. When the exhaust air flow was set at the lowest setting (LO), the face velocity turbulence intensities ranged from 5-8% when the room ventilation was off. When the room ventilation was turned on, the turbulence intensities increased to a range of 8-16%. At the medium exhaust air flow (MED), the turbulence intensity also increased from a range of 2-5% to a range of 5-12% with the ventilation system off and on, respectively. For both of these exhaust air flows, the highest variability occurred on the left side of the hood, closest to the room supply air diffuser outlet. At the high exhaust air flow (HI), the turbulence intensity was noticeably less affected by the room air conditioning with a range of 2-5% and 3-5% with the ventilation system off and on, respectively.

Air Conditioner Diffuser Velocity Testing

The overall air flow of the ceiling mounted air conditioning system was 590 ft3/min (16.7 m^3/min). Since this unit was a recirculating unit, one 2 × 2 ft (61 × 61 cm) ceiling diffuser was drawing in air from the room while the second 2 × 2 ft diffuser was supplying conditioned air to the room (see Figure 1b). The average air velocity at the face of the supply and return diffusers was 1260 and 280 ft/min (6.42 and 1.42 m/s), respectively. The direction of throw for the supply diffuser was 30-40 degrees from horizontal which directed supply air along the ceiling and away from the hood face.

Tracer gas containment evaluation

The results of the tracer gas testing are shown in Table II. Leakage was primarily noted at the left side monitor location which was closest to the room air diffuser outlet and consistent with the area of highest turbulence intensity. The right side of the hood and mannequin BZ sample locations generally did not show significant increases in concentration across all conditions. However, slight increases in BZ concentrations were noted at the lowest hood exhaust air flow with the room air conditioner on. When the room air conditioner was turned on and the hood was set at the LO or MED exhaust air flows, leakage was noted for all replicates. Minimal leakage was noted at the HI exhaust air flow with the room air conditioner on. No leakage was detected at any hood exhaust air flow when the room air conditioner was turned off.

Nanoparticle tracer containment evaluation

The results of the tracer nanoparticle testing are shown in Table II. Leakage was primarily noted at the left side sample location which was closest to the room air diffuser outlet and consistent with the tracer gas test results. The right side of the hood showed increases in particle concentrations (when the room air supply was on) but these levels were much lower than those exhibited on the left side of the hood. No increases in BZ concentrations were noted at the LO hood exhaust air flow and with the room air conditioner on but some increase in concentration above background was noted in the MED air flow. When the room air conditioner was turned on and the hood was set at the LO or MED exhaust air flows, leakage was noted for all replicates. Some minimal leakage was noted at the HI exhaust air flow with the room air conditioner on. No leakage was detected at any hood exhaust air flow when the room air conditioner was turned off for the MED or HI air flows but was noted for the LO hood exhaust air flow.

Nanopowder handling containment evaluation

The results of the nanoparticle containment testing are shown in Table II. During all nanopowder handling trials, no leakage was noted at any sampler location. This was consistent across all test conditions and replicates. In some cases, the particle concentration at the sample locations decreased during the trials leading to negative baseline corrected concentrations. This is due to the lack of leakage at the sample location along with the operation of the room air cleaner during each trial.

Test Results Summary

All test results are summarized in Table II. Average concentrations are shown by sample location, room supply air status (off vs. on), and hood exhaust flow. The Bonferroni multiple comparison test results show that statistically significant differences ($p > 0.05$) were found between exhaust flow level (LO, MED, HI) for the tracer gas and nanoparticle test only at the left side sample location. These differences were also only seen when the room air supply was on. Figures 4a and 4b show real time data for the tracer gas and nanoparticle test methods across a series of trials. As can be seen from these graphs, little leakage was identified when the room supply air was off except at the LO hood exhaust flow (Figure 4b). Figure 4a shows that the higher exhaust flows are associated with lower leak rates compared with lower exhaust flows (see Test Condition 2 [TC2] vs. TC3 vs. TC5). These differences are also clearly shown in Figures 5a, 5b, and 5c which show the average concentrations at the left side monitor for all three test methods.

DISCUSSION

This study evaluated three different test protocols for determining the containment effectiveness of a new nanoparticle ventilated enclosure. The tracer gas test protocol was adapted from the European standard using a small sintered metal disperser with a 10% SF_6/90% N_2 mixture at a flow of 2 L/min. The tracer nanoparticle test was developed using a low-cost particle generator from a common respirator fit test kit which utilizes a saltwater solution and atomizer. These two tracer tests gave similar results across a range of hood and room ventilation operating parameters. However, the nanoparticle tracer required that the background concentration was reduced using a room air cleaner. The use of an air cleaner resulted in room air background concentrations from 30-200 particles/cm^3 compared to typical concentrations on the order of 5,000-20,000 particles/cm^3 in indoor air. Further, the method used a lower cost detector than that used for the SF_6 tracer test.

Cesard et al. conducted experiments comparing the containment of a microbiological safety cabinet (MSC) using a tracer gas and nanoparticle method and found the results were well correlated.[14] That study was conducted under more controlled conditions inside a cleanroom with laboratory-based measurement equipment. This study conducted similar experiments and found consistent results with lower cost and generally available equipment in a laboratory setting. The use of a small commercially-available particle generator which only requires a power source and a standard salt solution makes the implementation of this approach more broadly applicable. For both studies, one of the key test parameters is to provide a low background of environmental (incidental) nanoparticles. For this study, the laboratory utilized a recirculation room air conditioning system with makeup air being introduced through an opening in the doorway. In a larger lab with significant outside makeup air, the ability to use a room air cleaner to reduce background particle concentrations to required levels may be difficult.

The nanoalumina handling test protocol has been used with success in previous laboratory settings to evaluate containment for a range of ventilated enclosures.[9, 15, 16] However, this method did not indicate leakage for any test condition in this study. This may be due to several factors including the general effectiveness of the control or the lower rate of particle emissions from the handling exercises compared to the particle generator. These pharmaceutical-based handling enclosures have been used successfully and characterized in vendor tests. In addition, the nanoparticle generation rate provided by the commercial particle generator is likely to be several orders of magnitude higher than that generated solely by handling processes. However, the use of these tracer methods helps determine design and operational conditions that may lead to failure of containment.

The sampling methodology is critical in accurately evaluating fume hood containment effectiveness. Recent studies have suggested that the ASHRAE 110 methodology may be insufficient for describing the containment effectiveness of the fume hood. [(17)] Tseng et al. evaluated airflow patterns in and around a conventional fume hood and noted the areas of greatest leakage occurred around the door sill and side posts of the hood. The flow patterns near the bottom of the hood exhibited unsteady 3-dimensional recirculation zones near the right corner and bottom opening of the hood. The authors suggest that containment leakage from these areas would be very likely given the highly turbulent flow fields in these regions of the hood. This leakage may not be identified using the ASHRAE 110 method because of the single point breathing zone tracer gas measurement protocol used in this method.

This study showed that leakage was identified in the regions near the hood sides even when the mannequin breathing zone did not indicate the leakage. The tracer gas and nanoparticle tests showed the greatest leakage on the side of the hood located closest to the room supply air diffuser. For all of the tracer gas and tracer nanoparticle tests, leakage was much more prominent on the left side of the hood although some leakage was noted on the right side and in the BZ sample locations. During the tracer gas and nanoparticle tests conducted in this study, leakage was primarily noted when the room air conditioner was on for both the LO and MED hood exhaust air flows. The tracer nanoparticle tests also indicated minimal leakage even at the HI hood exhaust air flow with the room air conditioner on. This indicates that the additional turbulence created by a diffuser above the hood can result in leakage even with face velocities in the range recommended by consensus standards.[(18)] When the room air conditioner was turned off, the static tracer gas tests generally showed good containment across all hood exhaust air flows. The nanoparticle tracer tests, however, indicated minor leakage for the LO hood exhaust air flow even when the room air conditioner was off although the amount of leakage was much less than when the unit was on (average concentrations of 57 pt/cm^3 vs. 2447 pt/cm^3).

Hood face velocity measurements showed that temporal variations increased when the room air conditioner was on resulting in an increase in turbulence intensity especially near the side of the hood adjacent to the supply air diffuser. Some researchers have suggested that high fluctuations in face velocity may adversely impact the performance of fume hood enclosures.[(19-21)] This study also showed that leakage was most likely to occur around the perimeter of the hood due to turbulence consistent with previous studies. [(19, 20, 22)] Altemose et al. noted that temporal fluctuations in face velocity were more strongly related to containment than spatial variation across the hood face.[(21)] They also found that the magnitude of cross draft velocities relative to hood face velocity is an important factor in determining whether a hood will leak. Other studies have also noted the impact of room air conditioning (or replacement air) on the performance of fume hood containment.[(21-23)]

Caplan and Knutson suggested that the terminal velocity of supply air jets is as important as hood face velocity in hood containment effectiveness noting that the center of the hood experiences better containment than the side positions of the hood.[22]

CONCLUSIONS

This study evaluated the containment effectiveness of a new nanomaterial handling enclosure using tracer gas, nanoparticle and nanopowder handling methodologies in a real-world laboratory setting. The use of a portable room air cleaner allowed the reduction in background nanoparticle concentration necessary for the tracer nanoparticle test. This test method used lower-cost generally available equipment to assess hood containment. The tracer gas and nanoparticle test results were well-correlated showing hood leakage under the same conditions and at the same sample locations.

Previous studies have successfully identified leakage in hoods using a nanopowder handling protocol similar to that used in this study.[15, 16] The nanopowder handling tests did not show leakage under any of the test conditions likely due to a variety of factors including overall hood containment effectiveness and lower particle emission rates. However, the handling test represents a more real-world approach to assessing containment under most conditions. More sensitive methods (such as the tracer gas and nanoparticle methods) can be used to evaluate design and operational factors important for good containment. The sensitivity of both tracer nanoparticle and handling methods is dependent on the ability to reduce the background nanoparticle concentrations to levels capable of detecting the escape of process generated particles. The tracer gas test benefits from the naturally low background of the tracer in the environment but requires more extensive instrumentation and expendables (e.g. gas cylinder, regulator). The nanoparticle method may provide a simple, effective way to characterize hood containment but should be further developed and assessed in a range of laboratory settings.

In this study, an average face velocity of 60 ft/min was not adequate to prevent the escape of tracer nanoparticles or tracer gas when the room air conditioner was on. Even at the medium exhaust flow, correlated with a face velocity of 80 ft/min, some face leakage was identified. Only at the highest face velocity of 100 ft/min was the hood effective regardless of room air conditioner operation. The influence of the room air conditioner was demonstrated with containment being adversely impacted during the use of room air ventilation. This effect was amplified at the low and medium hood exhaust air flows where hood face velocity temporal fluctuations were significant when the room air conditioner was on. At the highest exhaust air flow, the effect of the room air conditioner on face velocity fluctuations was minimal. In all test cases, the handling of nanopowders did not result in the release of measurable particles at the hood face or in the breathing zone of the operator. The testing conducted in this study is subject to the conditions of the hood (i.e. exhaust flow, interior equipment loading, etc.) and room (i.e. supply air location, proximity to doors/hallways etc.) and cannot be easily generalized. However, these results help inform considerations which must be made when testing or working with these hoods and reinforce the recommendations that supply air terminals be placed as far away from hoods and other exhaust devices as practical.[18]

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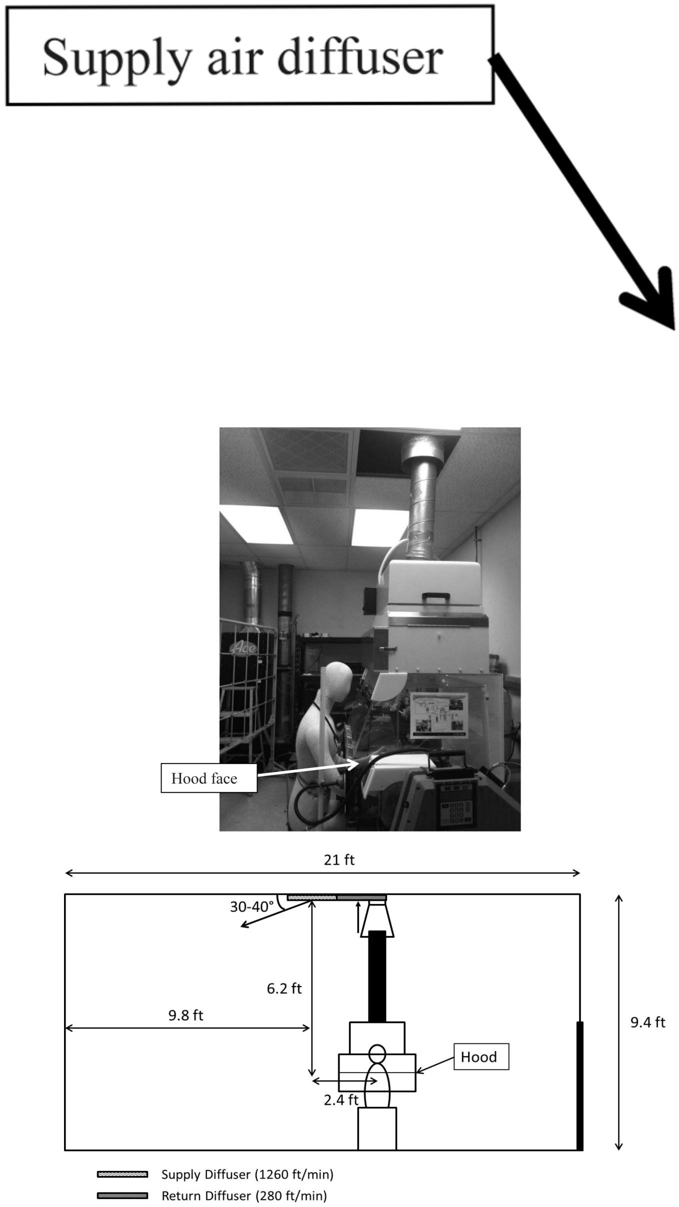

FIGURE 1.

Test room showing: 1) nanomaterial hood and room air diffuser and 2) view towards the front of hood showing room dimensions and air supply and return velocities.

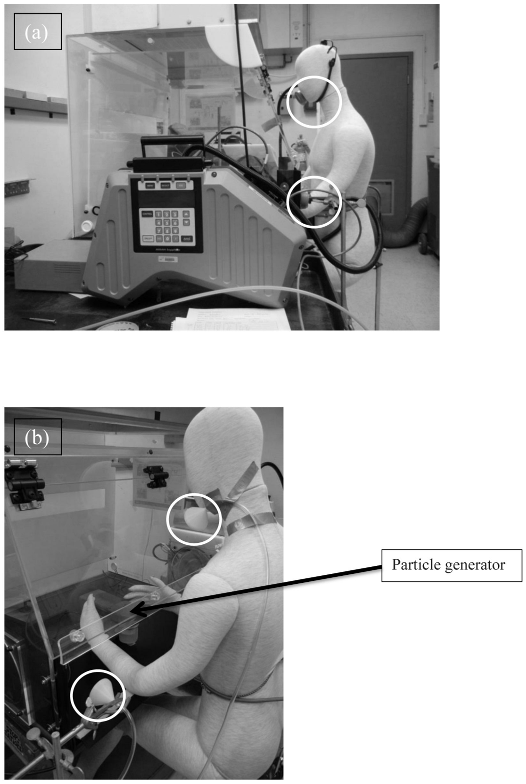

FIGURE 2.

Test setup showing mannequin and sampler locations for a) tracer gas test protocol and b) tracer nanoparticle test protocol. Sampler locations are highlighted in figure.

FIGURE 3.
Photo showing a) nanopowder handling test sample locations and b) conduct of tasks along with right side sampler and CPC. Sampler locations are highlighted in figure.

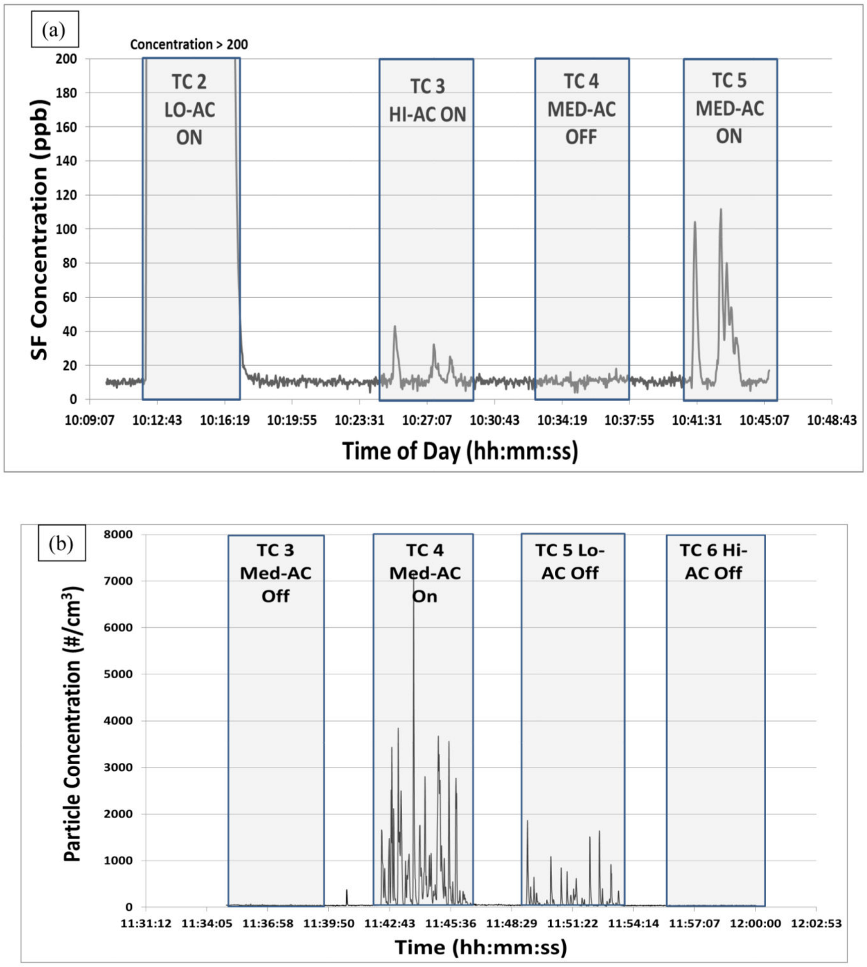

FIGURE 4.

Graphs showing the real time concentrations at the left sample location for a range of conditions for: a) the tracer gas test and b) the tracer nanoparticle test.

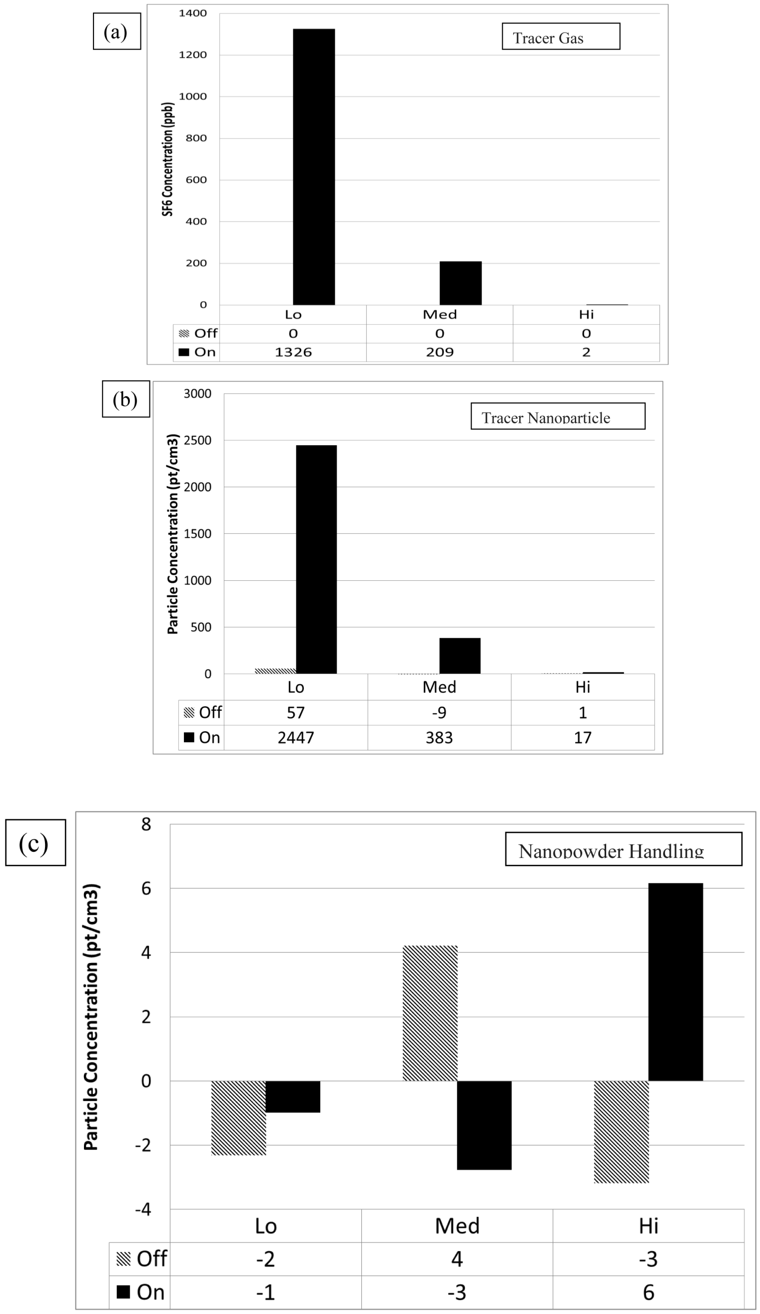

FIGURE 5.

Graphs showing the average concentration at the left sample location (with ac on and off) for: a) the tracer gas test and b) the tracer nanoparticle test, and; c) the nanomaterial handling test.

Note: The average concentrations when the room air supply is off do not show up well in Figures 5a and 5b due to the low levels compared to when the room air supply was on. The average concentrations are shown in the table below each figure.

Note: Negative particle concentrations were due to baseline corrections (i.e. room air particle concentrations decreased during test period).

TABLE I

Hood face velocity traverse measurements (in ft/min) and turbulence intensities with room ventilation on and off.

Sample Location	AC off						AC on					
	V_{LO} (fpm)	TI	V_{MED} (fpm)	TI	V_{HI} (fpm)	TI	V_{LO} (fpm)	TI	V_{MED} (fpm)	TI	V_{HI} (fpm)	TI
1--Left Side	49	8.51%	73	4.72%	89	5.38%	55	16.91%	64	12.33%	105	4.87%
2	56	5.62%	74	5.33%	95	3.70%	74	5.82%	81	5.28%	112	5.15%
3	62	4.57%	81	3.05%	100	2.50%	66	8.64%	84	11.30%	101	3.32%
4	62	3.81%	80	3.33%	97	3.73%	62	8.45%	93	5.58%	109	3.56%
5	62	5.69%	81	4.56%	100	2.14%	65	11.26%	87	7.74%	109	4.16%
6	63	5.92%	84	2.12%	99	3.87%	65	8.06%	81	8.13%	103	4.74%
7--Right Side	63	4.30%	86	2.96%	100	3.84%	74	10.96%	88	4.96%	108	4.62%
Average (fpm)	60		80		97		66		83		107	

Note: TI= Turbulence Intensity, V_{HI} = air velocity at high exhaust airflow, V_{MED} = air velocity at medium exhaust airflow, V_{LO} = air velocity at low exhaust airflow

TABLE II

Average concentrations by sample location and test method corrected for baseline. Bonferroni multiple comparison test results show statistically significant differences in exhaust flow by sample location.

Sample Location	Hood Exhaust Flow	Tracer Gas (ppb) AC Status		Bonferroni Groupings	Tracer Nanoparticle (pt/cm^3) AC Status		Bonferroni Groupings		Nanopowder Handling (pt/cm^3) AC Status		Bonferroni Groupings
		Off	On		Off	On			Off	On	
Left Monitor	Lo	0	1326	A	57	2447	A		−2	−1	
	Med	0	209	B	−9	383	A	B	4	−3	A
	Hi	0	2	B	1	17		B	−3	6	A
Right Monitor	Lo	0	0	A	−6	42		A	−2	−1	A
	Med	0	0	A	−10	9		A	4	−3	A
	Hi	0	0	A	2	3		A	4	6	A
BZ Monitor	Lo	2	1	A	−5	−8		A	−3	0	A
	Med	2	0	A	−10	9		A	4	−4	A
	Hi	3	1	A	2	3		A	4	6	A

Note: Means with the same letter are not significantly different ($\alpha = 0.05$). Negative concentrations were due to baseline corrections (i.e. room air particle concentrations decreased during test period).