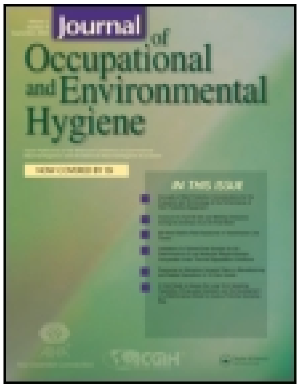

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Quantitative Evaluation of the Performance of an Industrial Benchtop Enclosing Hood

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Quantitative Evaluation of the Performance of an Industrial Benchtop Enclosing Hood

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Plain benchtop enclosing hoods are assumed to be highly effective in protecting workers from airborne contaminants, but there is little research published to support or rebut that assumption. The purpose of this research was to investigate the performance of a 36 in. wide, 30 in. high, and 40 in. deep benchtop enclosing hood. The study consisted of two parts: (1) investigating the effects of hood face velocity (five levels: 111, 140, 170, 200, and 229 ft/min) and wind tunnel cross-draft velocity (five levels: 14, 26, 36, 46, and 57 ft/min) on a plain benchtop enclosing hood, and (2) studying the effects of specific interventions (no-intervention, collar flange, bottom flange, cowling, and sash) added onto the same enclosing hood. A tracer gas method was used to study the hood's performance inside a 9 ft high, 12 ft wide, and 40 ft long wind tunnel. Freon-134a concentrations were measured at the mouth and nose of an anthropometrically scaled, heated, breathing manikin holding a source between its hands while standing at the enclosing hood's face. Roughly 3 L/min of pure Freon-134a mixed with 9 L/min of helium was released from the source during all tests. Results showed that hood face velocity, wind tunnel cross-draft velocity, and interventions had statistically significant effects ($p < 0.05$) on the concentrations measured at the manikin's breathing zone. Lower exposures were associated with higher face velocities and higher cross-draft velocities. The highest exposures occurred when the face velocity was at the lowest test value (111 ft/min), and the cross-draft velocity was at its lowest test value (14 ft/min). For the effects of interventions to the hood face, the results showed that flanges and the cowling failed to consistently reduce exposures and often exacerbated them. However, the customized sash reduced exposures to less than the detection limit of 0.1 ppm, so a similar sash should be considered when feasible. The hood face velocity should be at least 150 ft/min if a sash is not used.

Keywords enclosing hood, manikin, tracer gas, ventilation

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INTRODUCTION

In industry, benchtop enclosing hoods are used to control airborne contaminants in industrial processes such as welding, grinding, and spray painting of small parts. These hoods can be described as boxes with a plenum in the back leading to a tapered takeoff (Figure 1). Unlike laboratory hoods, they have no sash to prevent workers from leaning into the hood while performing tasks (Figure 2). It is plausible that exposures would be much higher if the worker's head were inside the hood.

The performance of an enclosing hood represents its ability to limit the exposure to the person using the hood. Little research has been done on plain enclosures, leaving many questions pertaining to their performance unanswered. Almost all published hood studies have been conducted on capturing hoods or laboratory hoods.(1–11) Because of the differences in airflow patterns induced by the sash of laboratory fume hoods, results from laboratory hood studies could be misleading if applied to plain enclosing hoods.

Various factors affect the performance of enclosing hoods.(1) Some depend on work practices, such as the arm movements of the user, and others are determined by the process, such as the generation rate of the contamination source. Some hood construction characteristics, such as the shape of the hood opening, could affect hood effectiveness. Furthermore, the location of a hood can expose it to disruptive cross-drafts across the face, especially if it is near air supply diffusers, doorways, windows, or aisles. Finally, operating parameters, such as exhaust flow rate and face velocity, have long been thought to be important to hood performance.(2)

Historically, evaluating hood performance has focused on measuring face velocity (V_{face}) and its distribution across the hood face. The 2010 edition of ACGIH®'s *Industrial Ventilation* manual (IVM) recommends 75 to 125 ft/min for "large" enclosing hoods and 100 to 150 ft/min for "small" hoods.(12)

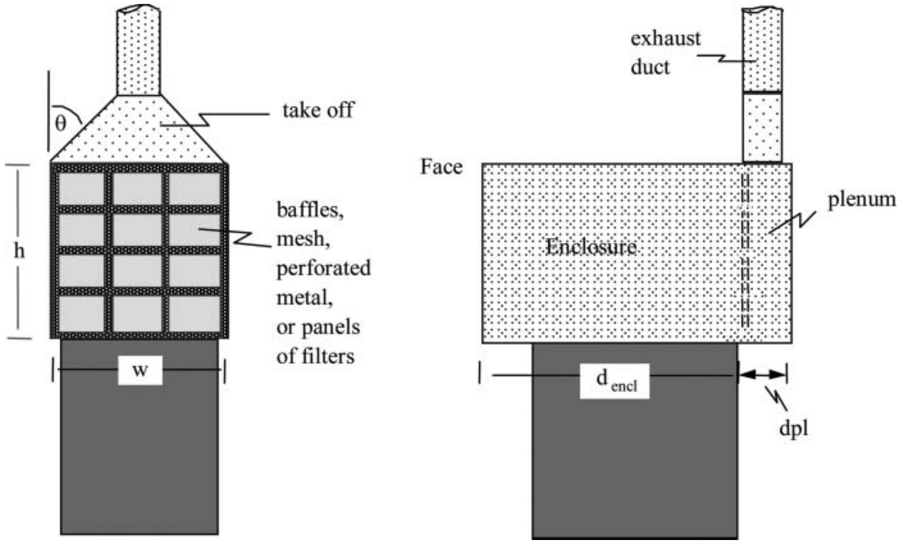

FIGURE 1. Benchtop enclosing hood.

However, most studies of laboratory fume hoods have shown weak correlations between levels of V_{face} and hood protection factors.[3–6]

In what may be the only published study of the effectiveness of a plain enclosing hood, Guffey and Barnea[13] found that hood face velocity was the dominant factor affecting exposures at the breathing zone of a manikin standing at the face of the hood. Concentrations at the nose fell exponentially with increasing face velocities. They also concluded that exposures generally were substantially higher when the manikin's head and arms intruded into the hood than when they did not, especially when velocities were low. However, that research was conducted using an unheated manikin in the absence of a cross-draft. It is possible that body heat and cross-drafts could both strongly affect hood performance.

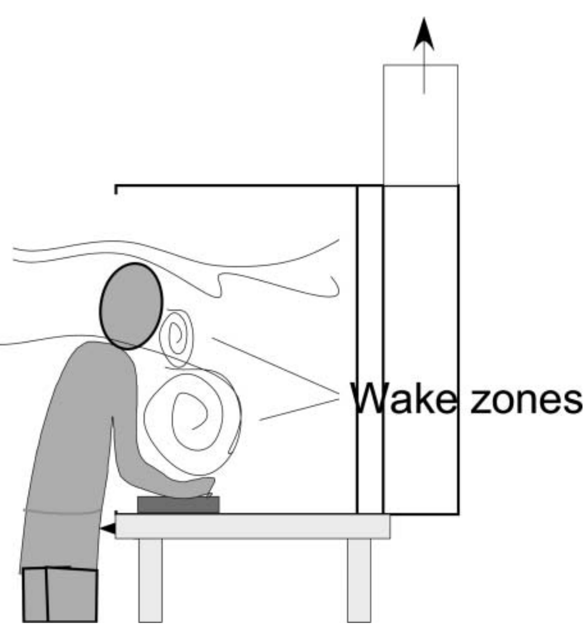

FIGURE 2. Wake zones in an enclosing hood.

The influence of room air currents is possibly as important as face velocity to effectiveness in controlling contaminants when a manikin is standing at the hood face. That seems to be the case with laboratory hoods since cross-drafts caused by external airflows, pumping doors, or by walking past a hood are believed to affect the performance of laboratory hoods.[14] It is not clear what level of cross-draft is acceptable for laboratory hoods.[7] Caplan and Knutson suggested that the cross-draft velocity should be less than 25% of the hood face velocity (i.e., < 25 ft/min).[8]

Li[15] and Yavuz[16] demonstrated with the same hood used in this study that the human body can be the dominating factor for local concentration distributions, especially in the breathing zone. Flow into the hood and past the user creates complex wake zones that can draw contaminant back toward the user, increasing exposures by as much as 200 times.[17] Wakes probably account for the dramatically higher concentrations when a manikin is present.[18] The air heated by the human body rises relatively rapidly, which adds further complexity to exposures.[19]

There is also wide agreement that airfoil sills are important to laboratory hood performance,[9] but that may not be true for plain hoods. Guffey and Barnea[13] reported that attaching flanges and tapered entries to a plain hood increased measured exposures. They speculated that the result in their study might have occurred because (1) the tapered inlets pushed the worker farther from the hood face and, since the source was kept in the manikin's hands, moved the source closer to the hood face, and (2) the flange and tapers were in direct contact with the manikin's thighs, effectively blocking upward flow between its belly and the hood.

Sulfur hexafluoride and dichlorodifluoromethane have been used as tracer gases in various hood studies.[1,4–6,10,13,20] However, both are harmful to the environment and are usually expensive. In this study, Freon-134a was mixed with helium for use as a tracer gas since it can be measured over a wide dynamic range with the Fourier transform infrared spectroscopy (FT-IR) used in this study.

In summary, the paucity of published studies of plain enclosing hood performance makes guidance to practitioners a matter of perceived plausibility rather than empirical science. This study investigated the effects of face velocity, cross-drafts, and hood face modifications to the hood face on the performance of a benchtop plain enclosing hood.

MATERIALS AND METHODS

The experiments were carried out in a wind tunnel that is 40 ft long, 9 ft high, and 12 ft wide (Figure 3). Uniformity of velocities in the wind tunnel was improved by the use of a bank of HEPA filters both at the face of the wind tunnel and at the plenum face. Constant temperature anemometry (CTA) measurements taken at 6-in. intervals vertically and 12-in. intervals horizontally along the cross-section of the wind tunnel showed a coefficient of variation of 10%. The average turbulent intensity was roughly 10% and was only 3–5% in the middle of the wind tunnel where the manikin stood in front of the test benchtop hood. The wind tunnel fan is controlled by a variable frequency drive, allowing a range of wind tunnel velocities of 10 to 155 ft/min. The combined cross-section of the full-sized enclosing hood and the manikin was less than 15% of the wind tunnel cross-section.

The enclosing hood has transparent plastic glass sides and top to allow observation inside the hood. The hood dimensions are 36 in. wide, 30 in. high, and 40 in. deep. To enhance velocity spatial uniformity, a perforated sheet face with 95% opacity is installed in the back of the hood. The takeoff is tapered 45 degrees in a typical square-to-round transition. The enclosing hood was located such that the manikin was near the midline of the wind tunnel (Figure 3).

The test manikin is a 66 in. high, anthropometrically scaled male with hollow cavities in the head, torso, legs, and arms. It has molded facial features and short, molded "hair," and it has rubber skin that feels reasonably like real skin. The manikin dimensions match with the 50th percentile for women and the 5th percentile for men. The manikin has joints in its shoulders, hips, and knees, which enables it to stand, sit,

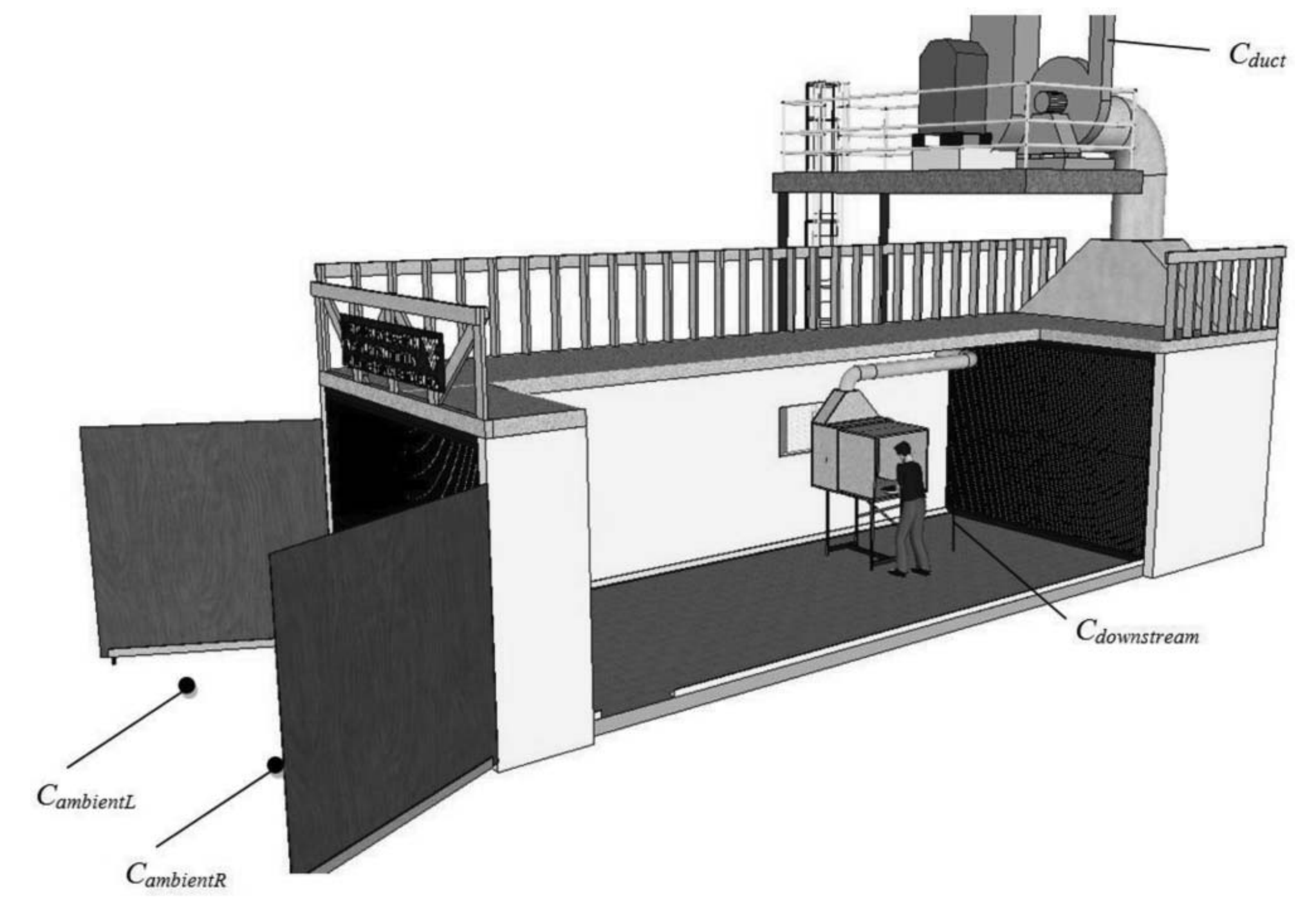

FIGURE 3. Overview of the wind tunnel with the enclosing hood placed inside.

and to pose in life-like postures. Heating the manikin head and torso to simulate the body heat of humans was done by placing strings of 1.5 watt lights within the torso and the head, for a total of 90 watts of power. The heating produced temperatures that were reasonably close to human values at the manikin's face (24–28°C) and back (34–38°C). The manikin was clothed with loose-fitting pants and a summer-weight short-sleeved shirt. Breathing by the manikin was simulated using a custom-made bellows device. Air was drawn in and expelled through the nasal openings, which were connected by 0.25 in. plastic tubing to 1 in.-diameter Teflon tubing. This air was heated to 36.7°C as it passed through the heated torso. A motorized bellows outside the wind tunnel provided a sinusoidal breathing pattern at roughly 0.4–0.5 liters per breath and 30–39 breathes per minute, which closely approximates the average breathing rate of 15 L/min reported for healthy adults.[21,22]

Temperatures of surfaces were measured with a calibrated infrared thermometer. Multiple points were measured on the manikin's cheek and torso, along with multiple points on the wind tunnel walls, ceiling, and floor. Air temperatures were measured with a calibrated dry bulb thermometer. Humidity was determined from a battery-powered psychrometer, and barometric pressure was measured with a standard laboratory mercury barometer.

A tracer gas used in this study was Freon-134a mixed with helium in a roughly neutrally buoyant mixture. Tracer gas was released through a 9-in. pie pan that was placed along the centerline on the floor of the hood with the outer edge located 1 in. from the hood face. Based on a previous study,[13] this position for the source provided the greatest challenge to the hood. It is also likely to be a position commonly used in this type of hood. Unlike lab hoods, plain hoods have no sill or vertical sash to help enforce rules to keep the source well inside the hood. Prior to the study, several subjects were asked to adjust the source to the position they favored. The positions selected were all close to the face of the hood.

The pie pan was covered by a plastic glass through which 99 uniformly spaced holes were drilled, each 0.05 in. diameter. Roughly 3 L/min of pure Freon-134a was mixed with 9 L/min of helium and released from the source during all tests. Assuming perfect mixing inside the hood, the challenge rate of Freon-134a was calculated from the ratio of the Freon-134a releasing rate to the hood exhaust air volume rate. For instance, the challenge rate was 127 ppm at the lowest tested V_{face} (111 ft/min) and 62 ppm at the highest tested V_{face} (229 ft/min), respectively.

During each test, the manikin's hands were placed on each side of the 9-in. pie pan in a manner intended to simulate a "working" posture at the hood face. As shown in Figure 3, samples were taken at the manikin's nose (C_{nose}) and mouth (C_{mouth}), outside the wind tunnel inlet ($C_{ambient}$), downstream of the wind tunnel ($C_{downstream}$), and at the hood exhaust duct (C_{duct}). Each sample was collected for 20 min, and all locations were sampled concurrently by drawing air at 0.2 L/min into 5-L plastic sampling bags (SKC Quality Sample Bag 237 Series, SKC Inc., Eighty Four, Pa.). Sampling volumes were roughly 4 L each.

After sample collection, each sample was analyzed for Freon-134a concentrations using a Gasmet Fourier transform infrared (FT-IR) gas analyzer (DX-4015; Gasmet Tech Inc., Helsinki, Finland) to determine its concentration. The FT-IR was frequently calibrated using 2 ppm, 10 ppm, 100 ppm, and 200 ppm span gases (Air-Gas, Morgantown, W.Va.).

Study Design

This study consisted of two parts: Study I and Study II.

- Study I tested the performance of the plain hood without any intervention. Two factors were investigated: hood face velocity (V_{face}), and wind tunnel cross-draft velocity (V_{cross}). Test conditions included every combination of five predetermined hood velocities: 111, 140, 170, 200, and 229 ft/min, and five cross-draft velocities: 14, 26, 36, 46, and 57 ft/min. Roughly 60 min were required for each test (40 min for sampling, and 20 min for FT-IR sampling analysis). Each of the 25 test combinations was tested twice in a single randomized order.
- Study II was conducted to determine the effects of flanges, cowling, and sashes added to a plain enclosing hood. The test methods and apparatus were the same as Study I. Test conditions included every combination of the three hood velocities (111, 170, and 229 ft/min), two cross-draft velocities (14 and 46 ft/min), and five intervention conditions: no-intervention, collar-flange, bottom-flange, cowling, and sash (Figure 4). Each condition was tested twice, for a total of 60 tests.

Data Analysis

Descriptive and inferential statistical analyses were performed using SAS version 9.2 (SAS Institute Inc., Cary, N.C.). The dependent variables were concentrations measured simultaneously at the manikin's nose (C_{nose}) and mouth (C_{mouth}), and the independent variables were enclosing hood face modifications (Intervention), as well as the levels of V_{face} and V_{cross}. Paired *t*-tests and linear regression were used to compare the differences between C_{nose} and C_{mouth}. Analyses of variance (ANOVA) were performed to study the effects of the independent variables and their interactions on the measured concentration values. All pairwise multiple comparisons were performed using the Tukey's range test.

RESULTS AND DISCUSSION FOR STUDY I

Five levels of hood face velocity and five levels of wind tunnel cross-draft velocity were utilized to evaluate the performance of the plain enclosing hood. The study was a completely randomized factorial design, in which each test condition was done twice (two replications). Concentrations were measured at five locations: nose (C_{nose}), mouth (C_{mouth}), outside the wind tunnel ($C_{ambient}$), downstream of the wind tunnel ($C_{downstream}$), and at the exhaust duct (C_{duct}). All values

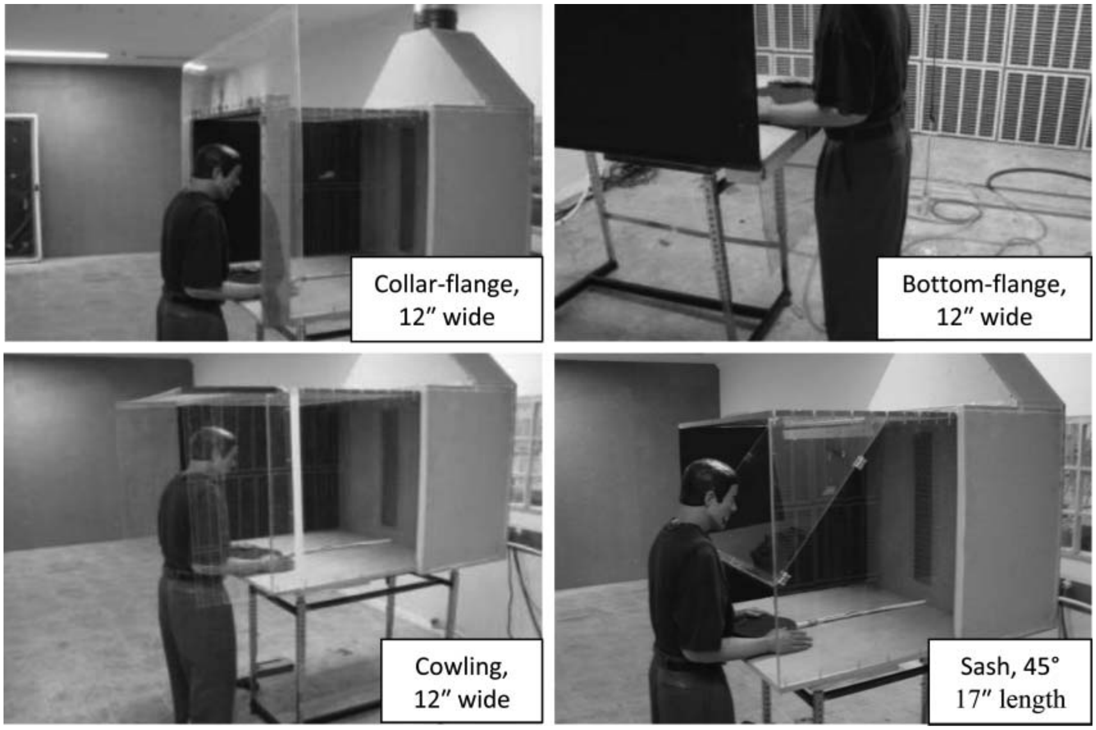

FIGURE 4. Interventions added to the enclosing hood.

of $C_{ambient}$ were near zero, thus it was not necessary to "correct" for ambient concentration. $C_{downstream}$ also was found to be zero or trivial in all cases.

Comparison of C_{mouth} to C_{nose}

Two samples were taken simultaneously at the manikin's mouth and nose locations. Plausibly, there would be only small differences between C_{mouth} and C_{nose} because they are close to each other. As shown in Figure 5, it is clear that the two dependent variables were highly correlated ($R^2 = 0.91$) with a linear regression slope of 0.9986, though outlying values inflate the correlation. The paired *t*-test revealed that concentrations measured at the two locations were not significantly different ($p = 0.18$). Therefore, the average of the concentrations at the mouth and nose (C_{BZ}) were used to represent the overall exposures received by the manikin at its breathing zone. The C_{BZ} values were log-transformed to meet the requirement for normal residuals in the statistical analysis.

Effect of Hood Face Velocity (V_{face})

Five levels of hood face velocity were investigated: $V_{face} =$ 111, 140, 170, 200, and 229 ft/min. As expected, V_{face} appeared to have a statistically significant effect ($p < 0.0001$) on the values of C_{BZ} (Table I), with higher levels of V_{face} associated with lower C_{BZ} values (Figure 6). This result is consistent with several published studies.[1,4,8,10,23] The highest C_{BZ} value was roughly 35 ppm; it occurred at the lowest hood face velocity (111 ft/min) and lowest V_{cross} value (14 ft/min). Conversely, the lowest value of C_{BZ} (~ 0 ppm) occurred at the highest level of V_{face} (229 ft/min). As shown in Figure 6, values of C_{BZ} were highly variable at all levels of V_{face} and V_{cross}, but the range of values was much broader for the lowest levels of V_{face} (111 and 140 ft/min).

Effect of Wind Tunnel Cross-Draft Velocity (V_{cross})

Five levels of cross-draft velocity were studied: 14, 26, 36, 46, and 57 ft/min. Concentrations downstream of the wind tunnel ($C_{downstream}$) were measured at values below the detection limit of the FT-IR (0.1 ppm), suggesting that little or no contaminant was drawn out of the hood, even at the highest cross draft velocity. Visualizations using both smoke and helium-filled bubbles confirmed that little contaminant would have been drawn out of the hood. In addition, the C_{duct} measurements did not show substantial differences for different levels of V_{cross} when the level of the V_{face} was fixed.

As shown in Table I, wind tunnel cross-draft velocity significantly affected the performance of the enclosing hood ($p < 0.0001$). Surprisingly, the lower values of V_{cross} were associated with the higher C_{BZ} values in every case (Figure 7), decreasing exponentially with increasing values of V_{cross}. Note in Table I that the interaction of V_{cross} and V_{face} was not statistically significant ($p > 0.09$). *Industrial Ventilation*[12] and many researchers studying laboratory fume hoods[7,8,11] have stated that even moderately high cross-draft velocities degrade hood performance, and for that reason, V_{cross} should be kept as low as possible. However, the results of this study do not support that assumption for the hood tested. One possible reason for the difference from laboratory hood study results

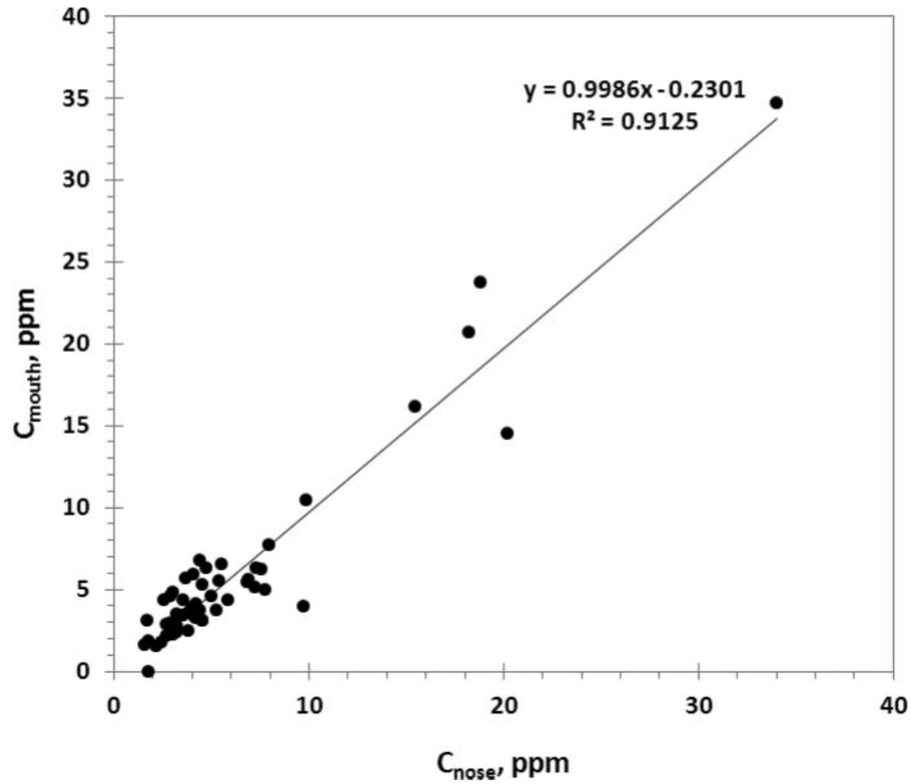

FIGURE 5. C_{mouth} versus C_{nose} for the plain enclosing hood.

is that laboratory hoods have aerodynamically shaped entries, while typical benchtop enclosing hoods generally have plain faces. In addition, the laboratory hood studies typically were done in laboratory rooms so that cross currents were complex. In this wind tunnel study the cross drafts always approached from the left side of the hood and manikin (Figure 3). This method of generating cross drafts should produce much less turbulence and non-uniformity of velocities than would be experienced if man cooling fans or diffuser grilles were stationed near the hood and their airflow directed to the vicinity of the hood, as was done in some laboratory hood studies.[4,8,10,20] Smoke tests on the tested enclosing hood showed that the wake from the hood's wall sometimes extended nearly to the hood user, with the extension varying with cross-draft velocity. The wake zones would likely have been different if different cross-draft velocity directions were tested.

RESULTS AND DISCUSSION FOR STUDY II

Study I established that hood face velocity (V_{face}) and wind tunnel cross-draft velocity (V_{cross}) are important factors affecting hood performance for the plain benchtop enclosing hood under the conditions tested. Study II was conducted to test the effects on the hood's performance when different interventions (i.e., modifications) were added (i.e., collar flange, bottom flange, and cowling) or just inside the hood (sash) (Figure 4). Each test condition was tested twice in random order. The goal for Study II was to determine whether these interventions with the hood improved its performance. The apparatus and methods were identical to Study I, except for adding the specific modifications to the hood.

Comparison of C_{mouth} to C_{nose}

As with Study I, two samples were taken simultaneously at the manikin's mouth and nose. Statistical analysis showed that the two dependent variables (C_{mouth} and C_{nose}) were less highly correlated ($R^2 = 0.87$) (and had a higher linear regression slope of 1.23) than those found with the unmodified hood face. As was done in Study I, the average of C_{mouth} and C_{nose} values were used to represent the concentrations (C_{BZ}) the manikin received at its breathing zone. Using C_{mouth} and C_{nose} separately had little effect on the significance of the different independent variables.

TABLE I. ANOVA on the Log-Transformed Values of C_{BZ} for the Plain Hood Study

Source	DF	ANOVA SS	Mean Square	F Value	p-value
V_{face}	4	1.721	0.430	27.52	<.0001
V_{cross}	4	1.790	0.448	28.63	<.0001
V_{face}*V_{cross}	16	0.433	0.027	1.73	0.0994

Notes: DF, degrees of freedom; SS = sum of squares.

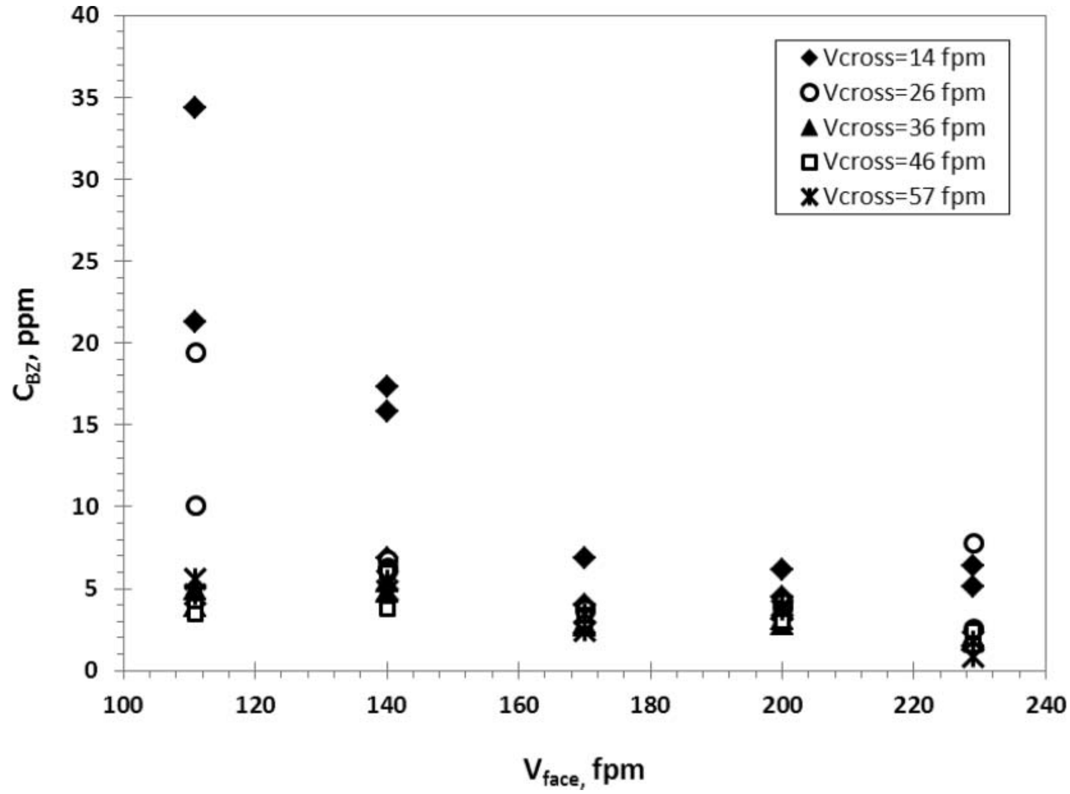

FIGURE 6. Hood face velocity vs. the C_{BZ} for the plain enclosing hood.

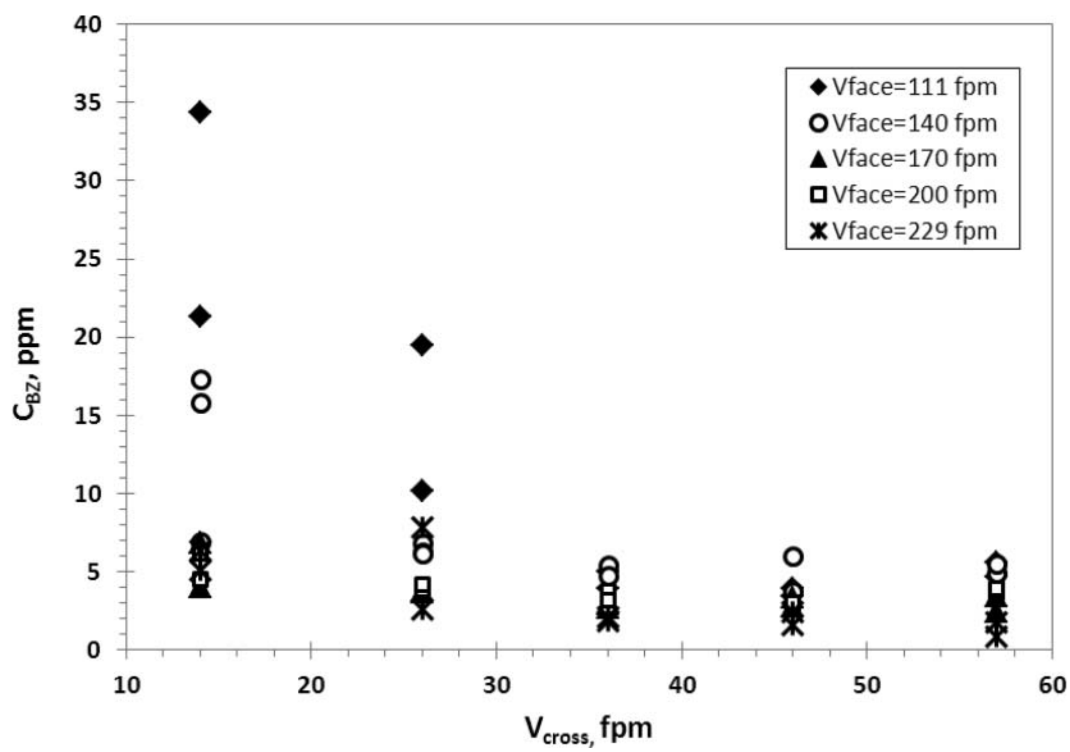

FIGURE 7. Wind tunnel cross-draft velocity vs. the C_{BZ} for the plain enclosing hood.

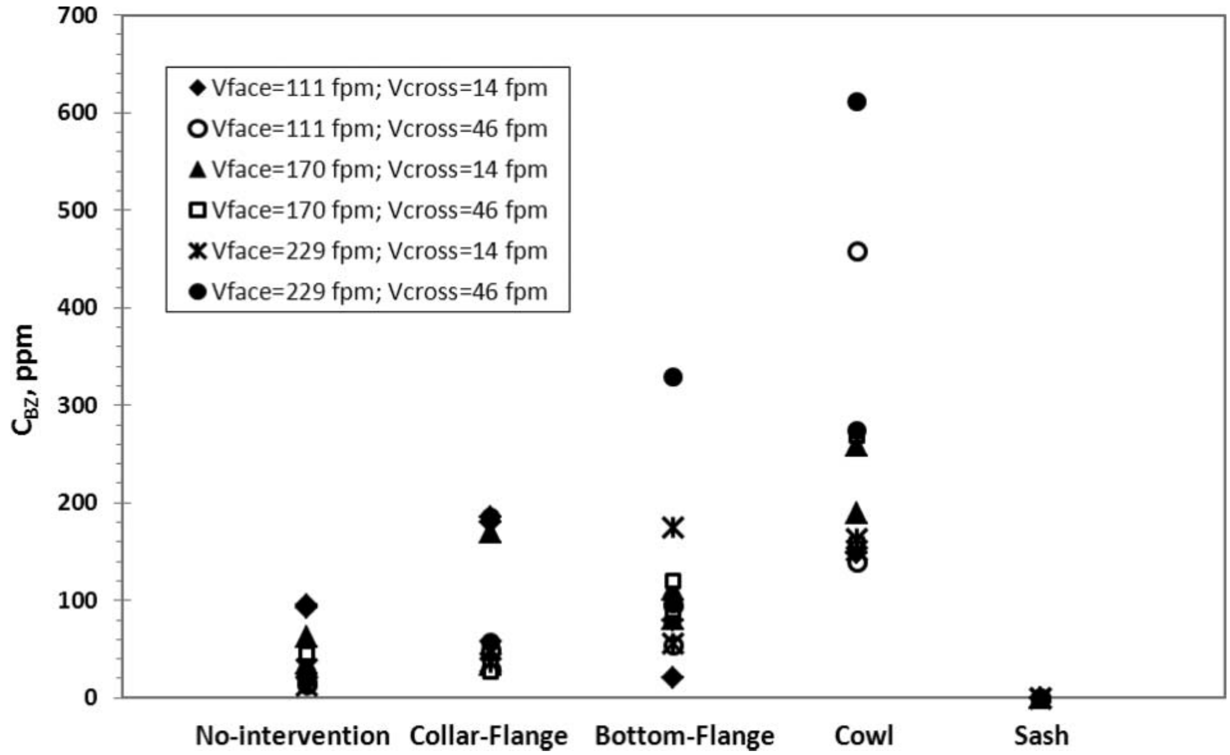

FIGURE 8. Interventions vs. the C_{BZ} for the modified enclosing hood.

Effects of Interventions

Five interventions: no-intervention, collar flange, bottom flange, cowling, and sash (see Figure 4), along with three levels of V_{face} (111, 170, 229 ft/min) and two levels of V_{cross} (14, 46 ft/min) were studied to determine the effects of interventions on the performance of the enclosing hood. Except when the sash was added, no other interventions clearly improved performance and for many conditions they made the hood performance worse than the no-intervention case. As shown in Figure 8, the hood with cowling produced the highest breathing zone concentrations compared to other interventions. Its C_{BZ} levels were almost one magnitude higher than those of no-intervention. A possible reason is that the cowling induced a substantial region of separation that enlarged the manikin's wake zone, increasing the transport of contaminant to the manikin's face. The average concentration values with flanges were greater than with no intervention, which is consistent with Guffey and Barnea.[13] However, several published laboratory hood studies reported that adding a bottom airfoil and flanges without acute angles would be beneficial to the hood performance.[9,20,24] However, the vertical sashes and the other details of construction likely make the aerodynamic performance of laboratory hoods quite different from the plain enclosure tested here.

The most important finding was that the sash reduced the concentrations dramatically. "Zero" exposures (i.e., below the detection limit of 0.1 ppm) were achieved for all combinations of V_{face} and V_{cross}. One possibility suggested by viewing smoke is that the custom sash reshaped the manikin's wake zone in a manner that separated it from the manikin's breathing zone. Another possible explanation is that the sash kept the worker's face separated from the contaminant, thereby sharply reducing exposures. Since the tested sash does not extend as far down as a laboratory hood sash (Figure 4), it should impede work less than a laboratory hood sash. Likewise, since the tested sash angled into the hood face, it should produce less glare and distortion than a vertical sash.

ANOVA results (see Table II) showed that the effect of adding interventions to the same enclosing hood was very significant ($p < 0.0001$) and that V_{face} and V_{cross} and their

TABLE II. ANOVA on the Log-Transformed Values of C_{BZ} for the Intervention Study

Source	DF	ANOVA SS	Mean Square	F Value	p-value
V_{face}	2	0.016	0.008	0.16	0.8540
V_{cross}	1	0.006	0.006	0.11	0.7465
V_{face}*V_{cross}	2	0.589	0.295	5.68	0.0095
Intervention	3	4.212	1.404	27.07	<.0001
V_{face}*Intervention	6	0.687	0.115	2.21	0.0774
V_{cross}*Intervention	3	0.561	0.187	3.61	0.0279
V_{face}*V_{cross}* Intervention	6	0.596	0.099	1.92	0.1194

TABLE III. Pairwise Comparison for the Interventions

Tukey[A] Grouping	Mean Log (C_{BZ}), ppm	Intervention
A	2.36	Cowl
A B	1.99	Bottom flange
B C	1.85	Collar flange
C	1.53	No-intervention
D	0.1[B]	Sash

Note: ANOVA with Tukey's range test.
[A]Means with the same letter are not significantly different.
[B]Value 0.1 ppm was used for statistical analysis when the measurements were under detection limit.

interaction did not achieve statistical significance ($p > 0.05$). The lack of significance for V_{face} and V_{cross} was probably due to the much greater variability in results when the several modifications were included. Of more interest is whether the interventions produced results that were significantly different from the unmodified condition. When the pairwise multiple comparisons were done for the difference among the mean of each separate intervention and the mean for the unmodified hood (see Table III), the differences between the cowling, no-intervention, and sash were statistically significant ($p < 0.05$). The cowling produced the highest C_{BZ} levels so it was significantly worse than the unmodified hood. The bottom flange and collar flange failed to reduce C_{BZ}. However, the sash was remarkably effective in reducing the exposure levels compared to the unmodified condition ($p < 0.0001$). The sash produced the lowest value of C_{BZ} for nearly all test conditions, suggesting that it is a robust solution for this hood under the conditions tested.

CONCLUSION

Study I results showed that for the plain hood the enclosing hood face velocity (V_{face}), wind tunnel cross-draft velocity (V_{cross}), and their interactions all had significant effects ($p < 0.05$) on log-transformed breathing zone concentrations (Log C_{BZ}). V_{cross} at the lowest level (14 ft/min) produced higher concentrations at the manikin's mouth and nose, which conflicts with common recommendations [(3)] that higher cross-draft velocities increasingly degrade hood performance. Higher face velocities were associated with lower C_{BZ}, as one would expect. Once V_{face} exceeded 170 ft/min and V_{cross} exceeded 36 ft/min, the concentrations no longer declined substantially with increasing values of V_{face} and V_{cross}.

Study II found that collar flange, bottom flange, and a cowling increased manikin exposures compared to the unmodified hood. The sash dramatically reduced manikin exposures. The tested sash should have much less glare and should impede arm movements much less than a laboratory hood sash. Since it also dramatically reduced exposures, a similar sash should be considered for industrial benchtop enclosing hoods and used when feasible.

LIMITATIONS

This study was done in a wind tunnel with airflows that are more uniform than would exist in a workplace. The manikin did not move, and its arms and legs were not heated. Results may differ from results found with human subjects. Hence, the results found apply only to the conditions investigated.

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