Aerodynamics and containment performance of the air-curtain fume hood

R. F. Huang and H. D. Chen
National Taiwan University of Science and Technology

ABSTRACT

The aerodynamic characteristics of the specially designed "air-curtain chemical fume hood" are diagnosed by using the tracer gas concentration detection method. It is found that the air curtain properly setup across the sash opening allows almost no sensible exchange of momentum and mass between the flowfields of the cabinet and the outside environment. Standard SF_6 tracer gas concentration measurements following the ANSI/ASHRAE 110-1995 standard and the rigorous EN14175 protocol for both the static and dynamic tests show extra-ordinarily satisfactory hood performance. The leakage of the tracer gas can approach almost null (< 0.001 ppm). Particularly, when the hood is installed in a laboratory or building which the draft, human walking, and sash movement are severe or unavoidable, the currently developed air-curtain fume hood presents extremely superior containment performance to the conventional hood.

1. INTRODUCTION

Fume hoods are ventilated enclosures used in laboratories where hazardous materials are handled. An exhaust system is connected to the fume hood that draws room air through the hood's sash opening and ejects the mixture of contaminated air out of the laboratory. This enclosure has a movable sash that is positioned to protect the user and allow experiment manipulation. The "face velocity" (the area-averaged flow velocity across the sash opening) is the first considered by the designers for the containment performance of the hood (e.g., Fuller & Etchells 1979, Caplan & Knutson 1982, Ivany et al. 1989, Fletcher & Johnson 1992, Volin et al. 1998, Maupins & Hitchings 1998). The back baffle is another factor which drastically influences the distribution of the inlet velocity at the sash opening (Sanders 1984) and therefore is usually modified by investigators and manufacturers to improve the containment efficiency (Bell et al. 2003).

Even though the aforementioned techniques proposed by the investigators and manufacturers do improve the containment efficiency, the inherent global and local recirculation flow structures induced by the boundary layer separation or the blockage effect would still inevitably induce more or less turbulent dispersion of the contaminants, particularly when the fume hoods are under the influences of dynamic flow motions. Therefore, the purpose of this article is to provide alternatively an innovative design of fume hood which is based on completely different operation principle from the conventional ones. The flow arrangement and the geometric design are aimed to avoid the induction of the vortical flow structures and build up an effective isolation air curtain to obtain extraordinary low spillage of contaminants. The validation of containment performance of the newly developed fume hood is also reported.

2. EXPERIMENTAL METHODS

The quantitative containment tests can provide direct information of fume hood performance. Usually, a tracer gas (sulfur hexafluoride, SF_6) is delivered into the hood cabinet at a known rate and measurements of concentration are collected around the hood to determine gas escape. A pressure gauge, a needle value, and a calibrated rotameter are engaged to a piping system to control the flow rate of the SF_6 supply.

A number of national standards exist. The ANSI/ASHRAE 110-1995 "Method of Testing Performance of Laboratory Fume Hoods" (ASHRAE 1995) and EN 14175-3:2003 "Fume Cupboards Part 3: Type Test Methods" (EN 2003) are employed in this work to diagnose the hood performance and optimize the operation conditions of jet and suction velocities. The ANSI/ASHRAE 110-1995 is focused on the measurement of the SF_6 concentration in the breathing-zone of an operator by placing a mannequin in front of the hood. The test methodology of EN 14175-3:2003 incorporates the inner plane measurement (static sash test), outer plane measurement (sash movement test), and robustness test (walk-bys or gust test). The inner plane measurement was proposed to determine the local average of SF_6 concentration on six sampling regions (each region has an area of 20 cm × 20 cm) across the sash opening of the fume hood. The inner plane measurement is able to detect detailed containment leakage in the static sash situation. In this paper the results of the static sash test are reported. The ANSI/ASHRAE 110-1995 method uses neat SF_6 as the tracer gas. Since that the injection of high density gas (such as sulfur hexafluoride) favors vertical stratification with high tracer gas concentrations at bottom of the cabinet (Sandberg & Sjöberg 1983), therefore, the EN 14175-3:2003 protocol uses 10% SF_6 in N_2 as the tracer gas to reduce the density of the mixture. Besides, because the human body is a heat source with its own convective air flow, such flow therefore may act as a vehicle for contaminants released close to the body (Johnson et al 1996). Because the ANSI/ASHRAE 110-1995 standard uses non-heated mannequin and does not take the convective air flow into account, the tracer gas data obtained in this paper thus may not be valid for a human being.

3. RESULTS AND DISCUSSION

3.1 Static Tests Following ANSI/ASHRAE 110-1995 Standard

Figure 1 shows the typical time-evolution records of the SF_6 concentration measured by the detector probe placed under the nose of the mannequin at various combinations of jet and suction velocities when the mannequin is placed at the center position of the hood. The sash height is 60 cm. The levels 0.05 ppm and 0.10 ppm noted by the symbols AM (abbreviation of "as manufactured") and AI, AU ("as installed", "as used") in Fig. 1 denote the allowable concentration thresholds set up by the AIHA (2003). The SF_6 concentrations measured in the regimes of *under suction*, *concave curtain*, and *straight curtain* shown in Figs. 1(a), (b), and (c), respectively, appear to have very low average values less than 0.001 ppm, which is almost undetectable by the Miran SapphIRe^{TM} Infrared Analyzer (the lowest detectable concentration is 0.001 ppm). The variations of SF_6 concentration in Figs. 1(a), (b), and (c) are also ignorable because the maximum concentration values in Figs. 1(a), (b), and (c) are only 0.001 ppm, 0.002 ppm, and 0.006 ppm, respectively. However, the time evolving concentration of SF_6 shown in Fig. 1(d) for the *over blow* characteristic flow mode is fluctuating drastically and has abnormally large average and maximum values of approximately 27 ppm and 72 ppm, respectively.

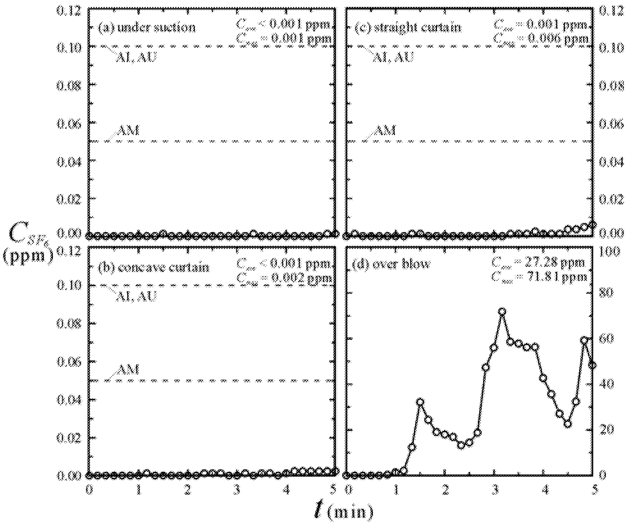

Fig. 1 Measured time-evolving results of SF_6 concentration of air-curtain hood following ANSI/ASHRAE 110-1995 Standard. (V_s, V_b) = (a) (6, 1) m/s, , (b) (10, 1) m/s, (c) (12, 4.5) m/s, (d) (6, 4.5) m/s.

Table 1 shows the statistics of the measured average SF_6 concentrations at H = 60 and 30 cm. It is interesting that all the cases measured in the regimes of *under suction*, *concave curtain*, and *straight curtain* are negligibly small: most of them are less than 0.002 ppm and few have values of 0.003 ppm, which are drastically lower than the thresholds of AM = 0.05 ppm. Even at V_b = 0, where the auxiliary jet is not applied, the detected SF_6 concentrations still remain to be at the same level as the air-curtain isolated cases. This is because the suction slot is located near the ejector which is placed at the lower level only 33 cm from the working surface and the detector probe is placed at the higher level of 66 cm far away from the working surface. This result, however, does not assure that the containment spilling out of the sash opening from other regions or locations can be sensitively detected. The concentrations measured at the *over blow* characteristic flow mode are all extraordinarily high at both sash heights. The measured results at the left and right sides of the hood are shown in Table 2. The SF_6 concentrations remain to be at the same level as that measured at the center. The three-dimensional flow structure appearing near the lower corner of the side pole as shown in Fig. 8 seems not to cause significant containment spillage. The reason may be because that the three-dimensional flow structures existing around the side poles are isolated outside of the cabinet by the air curtain so that the leakage of containment is alleviated.

Table 1 Results of tracer gas concentration measurements of air-curtain hood following ANSI/ASHRAE 110-1995 standard. Mannequin and ejector at center positions.

V_s (m/s)	V_b (m/s)	C_{ave} (ppm)
6	0	< 0.001
6	1	0.001
8	2	0.001
8	3	< 0.001
10	1	< 0.001
10	2	0.002
10	3	0.001

Table 2 Results of tracer gas concentration measurements of air-curtain hood following ANSI/ASHRAE 110-1995 standard.

V_s (m/s)	V_b (m/s)	C_{ave} (ppm)
6	2	0.001
8	0	0.001
10	0	0.001
10	1	0.002
10	2	< 0.001
10	3	0.001

For comparison, the results of the conventional fume hood corresponding to the Berkeley hood, the conventional fume hood corresponding to the Berkeley hood, the air-curtain hood, and the conventional fume hood corresponding to the present air-curtain hood are summarized in Table 3. The data of the Berkeley hood and the conventional hood corresponding to the Berkeley hood are reproduced from Tschudi et al. (2004). The tracer gas concentrations listed in Table 3 for four hoods are all far below 0.05 ppm of the AM threshold proposed by AIHA. It seems that the conventional hood which doesn't use the by-pass, airfoil, streamlined doorsill, etc. (e.g. the one used for purpose of comparison in this study) still can attain a containment spillage level detected far below the AM threshold, although their leakage level is higher than the modified ones. The concentration levels of the Berkeley hood are much improved when compared with its corresponding conventional hood and the conventional hood corresponding to the present air-curtain hood. The concentration levels of the present air curtain-isolated hood are about the same levels as the Berkeley hood. However, the maximum concentrations measured in the Berkeley hood and the conventional fume hood corresponding to the Berkeley hood seem to be apparently larger than those of the air-curtain hood.

Table 3 Results of tracer gas concentration measurements of (1) air-curtain hood and (2) conventional hood Tests performed according to ANSI/ASHRAE 110-1995 standard. H = 60 cm.

Test	Air-Curtain Hood		Conventional Hood	
	C_{ave} (ppm)	C_{max} (ppm)	C_{ave} (ppm)	C_{max} (ppm)
Center	< 0.001	0.001	0.007	0.022
Left	< 0.001	0.001	0.009	0.014
Right	0.002	0.003	0.008	0.013

Table 4 Results of tracer gas concentration measurements of air-curtain hood following ANSI/ASHRAE 110-1995 standard. H = 60 cm. Lower arms of Mannequin inserted horizontally into cabinet.

V_s (m/s)	V_b (m/s)	C_{ave} (ppm)
6	1	0.001
6	2	0.001
6	2.5	< 0.001
8	0	< 0.001
10	0	< 0.001
10	1	0.003
10	2	0.001
10	3	0.003

Table 4 shows the measured SF_6 concentrations of the air-curtain hood when the lower arms of the mannequin are inserted horizontally into the cabinet. The data do not show any particular difference from those obtained in Tables 1 and 2. When operating the air-curtain hood in the regimes of *under suction*, *concave curtain*, and *straight curtain* characteristic flow modes, the presence of the arms of the mannequin in the cabinet does not change the results of the tests with mannequin's arms hanging asides and downwards.

3.2 Static Tests Following EN 14175-3:2003 Protocol

As discussed in the section of Introduction, the shear layers along the separated boundary layers and the vortical flow structures existing around the peripherals of the sash opening are the most critical sources for mass and momentum exchanges with the outer environment. The strategy of the inner plane measurement method of the EN 14175-3:2003 protocol is quite different from that of the ANSI/ASHRAE 110-1995 Standard which emphasizes on the detection of the hood operator's breathing zone. It is aimed at the detection of hood leakage in the local areas covering the whole sash opening so that the most critical areas for containment leakage are included.

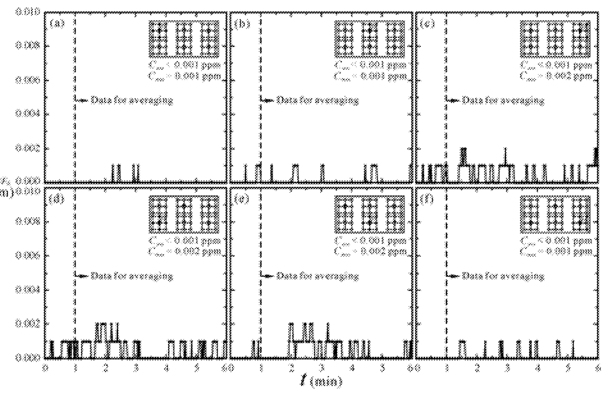

Fig. 2 Measured time-evolving results of SF_6 concentration of air-curtain hood following inner plane measurement of prEN 14175-3:2003 protocol. (V_s, V_b) = (6, 1) m/s, H = 50 cm. Characteristic flow mode is *under suction*. (a) P1, (b) P2, (c) P3, (d) P4, (e) P5, (f) P6.

Table 5 Results of tracer gas concentration measurements of (1) air-curtain hood and (2) conventional hood following EN 14175-3:2003 protocol. H = 50 cm.

Grid	Air-Curtain Hood			Conventional		
	C_{ave} (ppm)	C_{max} (ppm)			C_{ave} (ppm)	C_{max} (ppm)
P1	< 0.001	0.001			0.021	0.052
P2	< 0.001	0.001			0.081	0.151
P3	< 0.001	0.002			0.032	0.063
P4	< 0.001	0.002			24	46
P5	< 0.001	0.002			27	52
P6	< 0.001	0.001			31	44

The time-evolving SF_6 concentrations of the air-curtain hood at H = 50 cm, V_s = 6 m/s, and V_b = 1 m/s recorded by following the EN 14175-3:2003 protocol are shown in Fig. 2. The measured instantaneous values at all grid positions do not fluctuate drastically and the average and maximum values are relatively low. The average and maximum SF_6 concentration values measured for the operation conditions of (V_s, V_b) = (6, 1) m/s and (10, 1) m/s of the air-curtain hood and the conventional hood corresponding to the air-curtain hood are listed in Table 5. The detected average and maximum values of the air-curtain hood are within the limit of 0.001 ppm and 0.003 ppm, respectively. The average and maximum values of the conventional hood corresponding to the air-curtain hood are notably larger than those of the air-curtain hood: the average concentration value of the grid positions P1 ~ P3 on the upper rows is about 0.05 ppm, while the average concentration value of the grid positions P4 ~ P6 on the lower rows is about 27 ppm. The measured maximum concentrations also present high values because of large fluctuations. Apparently, the containment performance of the air-curtain hood is superiorly better than that of the corresponding conventional hood. Although there are no test data available for the Berkeley food following the EN 14175-3:2003 protocol, a reasonable inference can be made from the comparisons of Table 5 that the vortex-isolation technique employed by the Berkeley hood should have positive effects on reducing the containment leakage by isolating the shear layers which are induced by the separated boundary layers evolving from the bottom edge of the sash and the outer edge of the doorsill by using the planar jets issued from the bottom of the sash and the outer edge of the doorsill.

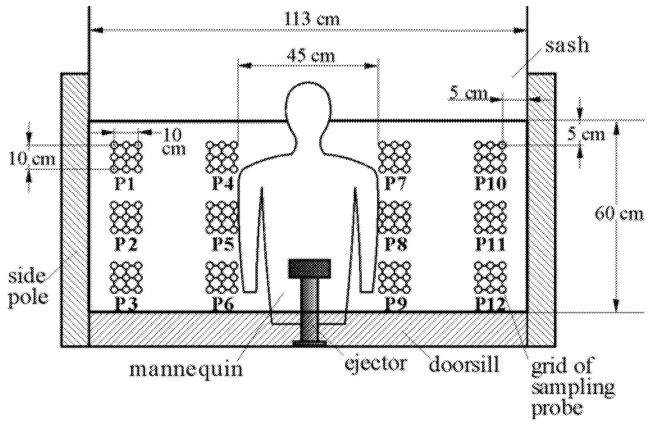

Fig. 3 Deployment of ejector, mannequin, and grid of sampling probes by using hybrid method. H = 50 cm.

In order to examine the influences of the chest wake as the mannequin presents, experiments by using a hybrid method, as shown in Fig. 3, are conducted in this study. The ejector and the mannequin follow the ANSI/ASHRAE 110-1995 Standard, while the grids of sampling probes follow the EN 14175-3:2003 Protocol. The tracer gas is 100% Sulfur Hexafluoride. The flow rate of the ejector is 4 L/min. The inner diameter of the sampling probe is 2.7 cm. The suction velocity at the inlet of the suction probe is 4.5 cm/s. The inlets of the sampling probes are on the sash plane. The results of using the hybrid method are shown in Table 6. The measured SF_6 concentrations of the air-curtain hood are not influenced by the presence of the mannequin, which corresponds to the arguments made according to the results of flow visualization shown in Fig. 1. While the results of the conventional hood corresponding to the air-curtain hood at the presence of the mannequin present drastically larger values of SF_6 concentrations at P2, P3, P6, P9, P11, and P12 than those when the mannequin is unoccupied. The potential of containment leakage induced by the mannequin wake and the peripherals of sash opening of the conventional hood is apparently higher than the air-curtain hood.

Table 6 Results of tracer gas concentration measurements of (1) air-curtain hood and (2) conventional hood following hybrid method. H = 50 cm.

Grid	Air-Curtain Hood		Conventional Hood	
			Without Mannequin	With Mannequin
		C_{ave} (ppm)	C_{ave} (ppm)	C_{ave} (ppm)
P1		0.002	0.022	0.031
P2		0.001	0.854	4.662
P3		< 0.001	1.143	25
P4		0.001	0.022	0.020
P5		< 0.001	0.023	0.023
P6		0.001	0.011	5.194
P7		0.001	0.021	0.044
P8		0.001	0.015	0.011
P9		< 0.001	0.086	11
P10		0.001	0.033	0.074
P11		0.001	18	21
P12		< 0.001	2.550	27

It is worthwhile to discuss the adequateness of the containment test by using the ANSI/ASHRAE 110-1995 protocol. From the results of the conventional fume hood corresponding to the air-curtain hood listed in Tables 3, 5, and 6, it is obvious that the fume hood which passes the ANSI/ASHRAE 110-1995 test may not pass EN 14175-3:2003 protocol because the contaminant leakages may occur in the regions other than the mannequin's breathing zone. Good containment measurement results obtained by following the ANSI/ASHRAE 110-1995 protocol do not guarantee the measurements taken at the regions other than the breathing zone being also under the threshold limit. Therefore, the test data derived from the ANSI/ASHRAE 110-1995 protocol may not be adequate for describing the effectiveness of a fume hood.

The flow rate required to generate 5 m/s of suction velocity is 0.21 m^3/s. The total flow rate required to generate 6 m/s of suction velocity and 1 m/s of jet velocity is 0.280 m^3/s. The suction flow rate of the conventional fume hood used in this experiment is about 0.35 m^3/s (which is not an exception for a high-performance fume hood on the market). The energy consumption by using the air-curtain fume hood is therefore approximately 20% ~ 40% lower than that of the conventional hood and is able to obtain extraordinarily higher containment performance even under the influence of environmental drafts. The wider the hood is, the larger the energy saving will be attained because the increase rate of the suction flow rate of the conventional fume hood is higher than that of the air-curtain hood as the hood width is increased.

4. CONCLUSIONS

An innovative air curtain-isolated laboratory fume hood is developed. The flow patterns and aerodynamic characteristics associated with the hood are phenomenologically studied. The containment performance of the air curtain-isolated laboratory fume hood is quantitatively validated by measuring the spillage concentration of SF_6 following the ANSI/ASHRAE 110-1995 Standard and the EN 14175-3:2003 protocol. By properly arranging the jet supply and the suction slot, it is possible to build up an air curtain across the sash opening of a fume hood. The air curtain is expected to isolate aerodynamically the possible spillage of the cabinet containment and the down-suction arrangement serves as an element of creating air curtain and the exhaust sink. The *over flow* characteristic mode presents large recirculation vortex in the hood cabinet and on the doorsill so that the operation considerations are ruled out. The vortices formed around the side poles and the doorsill are connected to the air curtain, instead of the interior containment as in the case of the conventional fume hood. Therefore the direct dispersion of the contaminants is alleviated and the necessity of employing streamlined doorsill or airfoil structure is avoided. Owing to the downward flow direction induced by the present arrangement of air curtain, the presence of a mannequin does not induce large recirculation vortex around the chest of the mannequin or create disturbance in the cabinet. When the tracer-gas concentration measurements are conducted following the ANSI/ASHRAE 110-1995 Standard and the interior measurement of the EN 14175-3:2003 protocol for the static sash condition, the average and maximum leakage levels of SF_6 concentrations of the air-curtain fume hood can be in the order of magnitude of 10^{-3} ppm or less even at the low suction velocities provided the hood is not operated in the regime of *over blow*.

REFERENCES

AIHA (2003). *American national standard – laboratory ventilation*. Fairfax: American Industrial Hygiene Association.

ASHRAE (1995). *Method of testing performance of laboratory fume hoods.* Atlanta: American Society of Heating, Refrigeration and Air Conditioning Engineers Inc.

Bell, GC, Sator, D, and Mills, E (2003). *The Berkeley hood: development and commercialization of an innovative hood*. Berkely: Lawrence Berkeley National Laboratory.

Caplan, KJ and Knutson, GW (1982). A performance test for laboratory fume hoods. Am. Ind. Hyg. Assoc. J. 43: 722-727.

EN (2003). *Fume cupboards-parts 3: type test methods.* Bruxelles: European Committee for Standardization.

Fletcher, B and Johnson, AE (1992). Containment testing of fume cupboards-I, methods. Ann. Occup. Hyg. 36: 239-252.

Fuller, FH and Etchells AW (1979). The rating of laboratory hood performance. ASHRAE J. 21: 49-53.

Ivany, RE, First, MW, and Diberardinis, LJ (1989). A new method for quantitative, in-use testing of laboratory fume hoods. Am. Ind. Hyg. Assoc. J. 50: 275-280.

Johnson, AE, Fletcher, B, and Saunders, CJ (1996). Air movement around a worker in a low-speed flow field. Ann. Occupational Hygiene, 40: 57-64.

Maupins, K and Hitchings, DT (1998). Reducing employee exposure potential using the ANSI/ASHRAE 110 method of testing performance of laboratory fume hoods as a diagnostic tool. Am. Ind. Hyg. Assoc. J. 59: 133-138.

Sandberg, M and Sjöberg, M (1983). The use of moments for assessing air quality in ventilated rooms. Building and Environment 18: 181-197.

Sanders, G.T (1984). A no-cost method of improving fume hood performance. American Laboratory, 10: 102-103.

Tschudi, W, Bell, GC, and Sartor, D (2004). *Side-by-side fume hood testing: ASHRAE 110 containment report (LBID-2560)*. Berkely: Lawrence Berkeley National Laboratory.

Volin, CE, Joao, RV, Reiman, JS, Party, E, and Gershey, EL (1998). Fume hood performance: face velocity variability inconsistent air volume systems. Appl. Occup. Environ. Hyg. 13: 656-662.