Effects of Doorsill Jet Injection on Fume Cupboard Containment

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The flow separation and its accompanied recirculation induced when the airflow passes over the inappropriately designed doorsill of a chemical fume cupboard are the key factors which would lead to deterioration of the cupboard performance. In order to alleviate the contaminant leakage of the fume cupboard induced by inherent aerodynamic deficiency, a technique using doorsill jet injection is developed and validated. A planar jet is ejected upward through a slot located across the inner surface of the doorsill of a full-scale, transparent fume cupboard and is ejected upward. The laser-light-sheet-assisted smoke flow visualization is performed to explore the physical mechanism of changing and controlling the flow structure. It is found that the upward injected jet is curved by the airflow drawn into the sash opening and forms a layer of clean air which can isolate the contaminant and alleviate the diffusion through the recirculating vortex on the doorsill, if the jet velocity is properly adjusted. The tracer gas concentration measurements present extraordinarily satisfactory results—the order of magnitude of the leakage of tracer gas near the doorsill may be reduced from original levels of $10^2$ to $10^2$ p.p.m. Except for the experimental fume cupboard used for development of technique, two commercial fume cupboards are employed for verifications and comparisons on the proposed method. Tests about the two modified commercial fume cupboards demonstrate good agreement to those of the model fume cupboard.

Keywords: flow visualization; fume cupboard; performance; tracer gas; turbulence; vortex

INTRODUCTION

A fume cupboard is designed to provide a solution for the protection of laboratory operators and the environment where manipulations of hazardous gases, fumes and particulates are required. The performance of a fume cupboard is determined by a complex interaction of factors such as the working chamber, the exhaust system, fume cupboard location, cross drafts, operational parameters, etc. Although the face velocity is conventionally considered as one of the important parameters which can affect the containment ability of the hazardous fumes and vapors, many studies (Fletcher and Johnson, 1992a,b; Saunders, 1993; Maupins and Hitchings, 1998; Volin et al., 1998; Ekberg and Melin, 2000) suggested that face velocity alone is a very poor indicator of fume cupboard containment because no correlation between the face velocity and the cupboard performance is observed.

Durst and Pereira (1991, 1992), Hu et al. (1996, 1998), Kirkpatrick and Reither (1998), Nicholson et al. (2000) and Lan and Viswanathan (2001) have conducted numerical analysis to predict flow patterns and the containment ability of fume cupboards. The key element in the flow phenomena of the fume cupboard was identified as the boundary layer turbulence, which manifested the physics in contributing to contaminant leakage. If the contaminants in the cupboard are recirculated to the area near the face of the cupboard, dispersion through the shear layer out to the environment via the turbulent diffusion mechanism would easily be possible.

Detailed experimental data on the physical mechanisms governing the leakage of contaminant were
investigated by the authors previously (Tseng et al., 2006, 2007). Very complex flow configurations, such as large-scale vortex structures and boundary layer separations, were found around the doorsill and the side pole of the fume cupboard. In the near-wake region of the operator, large recirculation zones and wavy flow structures were also identified. The results of tracer gas experiments showed that the areas with high contaminant leakages exactly correspond to where the flow recirculates or separates. These complex flow behaviors can easily contribute to the spread of contaminant leakage and increase the probability of laboratory workers’ exposure.

In order to alleviate the influence of the recirculated vortex structures and the boundary layer separations near the doorsill, in this research, a fresh air jet supplementation mechanism employing aerodynamic design concept is inserted at the interface between the contaminant leakage zone and the operator at the face of the cupboard. The mechanism simultaneously employs blow and suction flows, similar to the push–pull technology and the jet-in-cross flow technique, to enclose and isolate the vortices formed around the doorsill area and the operator’s wake zone in a fume cupboard. Systematic experimental works are conducted to probe flow characteristics of the vortex encapsulation cupboard in various suction and blow velocities. A smoke trajectory flow visualization method is employed to clarify the variations of flow field. The tracer gas measurements test of EN 14175-3:2003 method (CEN, 2003) is subsequently conducted to verify the containment of the vortex encapsulation fume cupboard, both in experimental and commercial models.

**EXPERIMENTAL ARRANGEMENTS**

**Fume cupboard for study**

The experimental setup, as shown in Fig. 1, includes a fume cupboard, an exhaust fan and instruments. The fume cupboard for study has an 850 × 1200 mm aperture, which is made of transparent acrylic plates, so that the laser beams can pass through for flow visualization. The fume cupboard consists of a baffle across the rear wall. The baffle has a top slot and a bottom slot to help effectively remove the contaminants through the cupboard. The top panel of the cupboard has an exhaust collar to connect the exhaust duct to the cupboard. An AC motor/centrifugal fan provides the suction of the cupboard. The suction flow rate is measured by a homemade venturi flow meter along with a calibrated pressure gauge. The error of the suction flow rate measurement is <1% of the reading. Measurement is conducted with the sash at a height of 500 mm.

Experiments are carried out in a well-controlled test room. The test room is a typical laboratory room with dimensions of 19 × 16 × 5 m. During the experiment, turbulence and interference from external sources such as air supply diffusers, doors and traffic in the room are restricted.

A slot which provides the jet flow (with an average velocity \( V_b \) in m s\(^{-1}\)) is arranged across the doorsill of the fume cupboard. The length of the slot is 1200 mm. Two slot widths, 5 and 10 mm, are tested. The flow driven by a cross-flow fan passes through the rectification section (including the honeycombs and mesh screens) to dissipate some turbulent energy and issue the jet through the slot. A miniature hot-wire anemometer, which is calibrated by a laser Doppler velocimeter, is used to measure and monitor the air jet velocity. The accuracy of the jet velocity measurement is ~0.5% of the reading. The distinct flow patterns and the capture zones are recognized under various specific blow and suction velocities.

**Flow visualization**

The flow visualization technique is used to detect the flow pattern and structure in the interior and on
the surface of the fume cupboard. The experimental apparatus for flow visualization is shown in Fig. 2. The paraffin oil mist is produced in the smoke generator and continuously seeded through the homemade smoke ejector into the test section. The diameter of the oil mist particles, measured by a Malvern 2600C particle analyzer, is $1.7 \pm 0.2 \mu m$. The density of this particle is $0.821 \text{ g m}^{-1}$. Without considering the effect of turbulent diffusion, the relaxation time constant is estimated to be $<7.7 \times 10^{-5} \text{ s}$ and the Stokes number is in the order of $10^{-6}$ within the range of experiment. Because the Stokes number is drastically smaller than unity, the seeded particles are estimated to be able to follow the flow fluctuations at least up to 10 kHz, according to the suggestion of Flagan and Seinfeld (1988).

The streams of the smoke are discharged by two different means: (i) For simulating the contaminant transport process, the smoke is released through a smoke ejector which is made following the EN 14175-3:2003 method for tracer gas measurement. Both the positioning of the smoke ejector and the release rate of the smoked flow follow the EN 14175-3:2003 protocol for tracer gas measurement. (ii) For better visualization of flow structure of the jet in some target regions, the smoke is released at various velocities through a stainless steel tube which has a diameter of 4 mm. The laser beam emitted from a Nd:YAG laser (Dpss Green Laser AMGC-100, Onset Electro-Optics Corp., Taipei, Taiwan) is transmitted through an optical fiber and connected to a 20° laser-light-sheet expander. The particle images are
recorded by a CCD camera (DCR-TRV 900, Sony Corp., Brussels, Belgium). The camera is equipped with an asynchronous variable electronic shutter, so that the exposure time can be adjusted from 1/12 000 to 1/30 s at a framing rate of 30 f.p.s.

Static tracer gas test following EN 14175-3:2003 protocol

Experiment is performed at the sash height ($H$) of 500 mm. The measurements are conducted in accordance with the EN 14175-3:2003 protocol by using 10% SF$_6$ in N$_2$ as the tracer gas, as shown in Fig. 3. The tracer gas ejector is a hollow cylinder made of sintered metal with a length 25 mm and a diameter 15 mm in accordance with this method. The release rate of the tracer gas is 2 l min$^{-1}$. By dividing the gas release rate by the exit area of the ejector, the average velocity of the gas at the outlet of the ejector is estimated to be 18.86 cm s$^{-1}$. Nine sampling probes are arranged in a grid based on a square area of 200 × 200 mm. There are three vertical and three horizontal grid lines separated from each other by 100 mm in both directions. The tracer gas ejector is arranged with its center in line and 150 mm from the center of the sampling probe grid. The axis of the central probe in the grid is in line with the midpoint of the ejector. The central sampling probe grids are positioned on the sash plane with its center probe at points formed by the intersection of three equally spaced lines between the horizontal boundaries of the

Fig. 4. Smoke patterns near (a) doorsill and (b) right side pole of fume cupboard without doorsill jet injection. Smoke released from smoke ejector, $V_o = 0.5$ m s$^{-1}$, $d = 10$ mm and $H = 500$ mm.
sash plane with the two outermost lines 130 mm from the horizontal boundaries. The sampling probes are connected to the sampling manifold by tubes of equal lengths. The detector probe is affixed to the output of the manifold. Tracer gas samples are taken through a stainless steel tube of 8 mm internal diameter, which is fitted with a diffuser of 30 mm internal diameter at inlet end of suction velocity 3.7 cm s$^{-1}$. Sampling is taken for 360 s.

The mean and peak value of SF$_6$ concentration are measured and recorded with a high-precision infrared detector (MIRAN SaphiRe Ambient Air Analyzer, Thermo Electron Corp., Franklin, MA, USA). The detection range from 0 to 4 p.p.m. is calibrated by the manufacturer and checked in the laboratory before use of the instrument. The detection range from 4 to 100 p.p.m. is calibrated in the laboratory. Separated calibration curves and regression formula are obtained for the ranges 4–37 and 37–100 p.p.m. The maximum deviations of the calibration curves from the supplied standard concentration values are 10% of the reading above the standard concentration for the range 0–1 p.p.m., 20% of the reading above the standard concentration for the range 1–4 p.p.m. and 12% of the reading below the standard concentration for the range 4–100 p.p.m. The output data of the instrument can be set on the control panel to ‘p.p.m.’ with a resolution of 0.01 p.p.m. or to ‘p.p.b.’ with a resolution of 1 p.p.b. In this study, the resolution is set to p.p.m. The sampling flow rate is 14 l min$^{-1}$. The internal sample rate of the detector is 20 Hz. The average value over a 10-s period is recorded as one reading.

Fig. 5. Smoke patterns near (a) doorsill and (b) right side pole of fume cupboard with doorsill jet injection. Smoke released from smoke ejector, $V_o = 0.5$ m s$^{-1}$, $V_b = 3.2$ m s$^{-1}$, $d = 10$ mm and $H = 500$ mm.
The tracer gas concentration measurements are conducted five times in the laboratory. For each run, the relative trends among different characteristic flow modes are quite similar. The maximum variation of the detected leakage concentration values among these five experiments is $<11.4\%$ of the average value. The data presented in this article are average of five experimental results.

RESULTS AND DISCUSSION

Flow patterns with/without doorsill jet injection

The flow patterns around the doorsill and side pole of the fume cupboard without doorsill jet injection are shown in Fig. 4a,b, respectively. When the flow passes over the doorsill and side poles of the cupboard, the boundary layers separate. The separated boundary layers evolve from the edges of the doorsill and side pole and entrain smoke in the cupboard due to the formation of recirculation bubbles, so that the regions near the doorsill and side pole are filled with dispersed smoke. Some vortical flow structures can be observed there. They appear to evolve from the complex dynamics of the three-dimensional turbulent flow.

Figure 5a,b shows the flow patterns around the doorsill and side pole, respectively, when the slot jet behind the doorsill is applied. The fresh air jet issued from the bottom level is impinged by the air drawn into the sash opening and therefore is curved inward. The curved jet isolates the smoke in the cupboard, so that no scattering light is observed outside the sash opening. It cuts off the path of entrainment of smoke in the cupboard by the recirculation bubbles shown in Fig. 4, so that no smoke is observed near the doorsill and the side pole. The large-scale recirculation zones originally observed near the doorsill and side pole in Fig. 4 therefore become almost invisible in Fig. 5. The doorsill jet injection seems to have effect of isolating the in-cupboard contaminant from outside environment.

Characteristic flow modes of doorsill jet injection

The flow patterns around the doorsill with the jet injection (smoke released through a smoke ejector) present three modes as shown in Fig. 6. In Fig. 6a for the jet-to-face velocity ratio $V_b/V_o = 2.0$, the jet is severely bent by the airflow drawn into the cupboard. The separated boundary layer evolving from the front edge of the doorsill entrains some jet fluids, so that smoke is visible in the recirculation bubble on the doorsill. The jet fluids entrained into the doorsill recirculation region may have dangers of mass exchange with the environmental air. This kind of flow is denoted as ‘under-blow’ mode.

At higher jet-to-face velocity ratio $V_b/V_o = 6.4$, as shown in Fig. 6b, the jet momentum is large, so that the bent angle becomes not severe. The jet issues to a height and is bent into the cupboard. No trace of smoke is observed on the doorsill, although vortical flow structures may still exist there due to the flow topology. The bent slot jet stands in between the in-cupboard contaminant and the outside atmosphere. The flow pattern seems to have better contaminant isolation effect than that of the under-blow pattern because almost all the smoke is encapsulated in the cupboard by the bent jet. We call this flow pattern the ‘transition’ mode.

At further higher jet-to-face velocity ratio $V_b/V_o = 12.4$, as shown in Fig. 6c, the jet momentum is high enough to resist the impingement of the airflow

Fig. 6. Smoke patterns near doorsill of fume cupboard with doorsill jet injection. Smoke released from smoke ejector (a) $V_o = 0.5\text{ m s}^{-1}$, $V_b = 1.0\text{ m s}^{-1}$ (under-blow), (b) $V_o = 0.5\text{ m s}^{-1}$, $V_b = 3.2\text{ m s}^{-1}$ (transition) and (c) $V_o = 0.5\text{ m s}^{-1}$, $V_b = 6.2\text{ m s}^{-1}$ (over-blow). $d = 10\text{ mm}$, $H = 500\text{ mm}$. 
passing through the sash opening. The jet issues to a high level, breaks up and disperses into turbulent flow. Some part of the jet fluids seems to be dispersed outward to the outside atmosphere. This phenomenon may provide an opportunity for the contaminant (which is entrained by the strong jet) to leak outward with the dispersion of the jet fluids. This type of jet flow is denoted as the ‘over-blow’ mode.
Table 1. Mean and peak values of SF$_6$ concentrations without doorsill jet injection

<table>
<thead>
<tr>
<th>Grid position</th>
<th>$V_o = 0.4 \text{ m s}^{-1}$</th>
<th>$V_o = 0.5 \text{ m s}^{-1}$</th>
</tr>
</thead>
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<tr>
<td></td>
<td>$C_{\text{ave}}$ (p.p.m.)</td>
<td>$C_{\text{max}}$ (p.p.m.)</td>
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<tr>
<td>P1</td>
<td>24.7</td>
<td>43.5</td>
</tr>
<tr>
<td>P2</td>
<td>22.1</td>
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<td>P5</td>
<td>0.024</td>
<td>0.022</td>
</tr>
<tr>
<td>P6</td>
<td>0.021</td>
<td>0.041</td>
</tr>
</tbody>
</table>

$d = 10 \text{ mm}, H = 500 \text{ mm}.$

It is apparent that operating the cupboard at the under-blow and over-blow characteristic modes may lead to fail of contaminant isolation near the doorsill and the higher locations, while operating the doorsill jet velocity in the transition regime may obtain a ‘clear’ zone around the doorsill. It is therefore proper to identify the characteristic flow modes for operating conditions. The three characteristic flow modes shown in Fig. 6 are identified in the domain of the jet and face velocities, as shown in Fig. 7 for the slot width $d = 10 \text{ mm}.$ The bands marked by short slashed lines (looking like a ‘distorted Y’) denote the uncertain regimes for identification between different characteristic regimes. The transition regime which fits the appropriate condition for operating the hood is located in between the two branches of the distorted Y.

If the slot width $d$ is reduced to 5 mm, the transition mode for proper operation shrinks to a small regime, as shown in Fig. 8. Since the jet width is reduced, the area-integrated jet momentum across the jet width (or force) is also decreased. The capability of withstanding the impingement of the airstream through the sash opening is weakened. The transition regime therefore is decreased.

The influence of sash height would be an important parameter for the operation of the doorsill jet. The partially closed sash and the accompanied increase of face velocity (if the hood has a constant air volume design) may cause interference and severe deflection of the doorsill jet. Therefore, more investigations on the effects of the sash opening and the corresponding variations of the operation parameters (e.g. $V_h$ and $V_o$) should be performed in the future.

Tracer gas diagnostics

The concentration of the SF$_6$ leakage without doorsill jet injection is shown in Table 1. Along the lower row near the doorsill (P1, P2 and P3), the detected leakage levels [either the average concentration of SF$_6$ ($C_{\text{ave}}$, p.p.m.) or the maximum concentration of SF$_6$ ($C_{\text{max}}$, p.p.m.)] are remarkably higher than those of the upper row near the bottom edge of sash (P4, P5 and P6). This phenomenon corresponds to the results of flow visualization as shown in Fig. 4. If the doorsill jet is applied, the leakage levels of SF$_6$ as shown in Table 2, no matter the characteristic flow mode is under-blow, transition or over-blow, become dramatically lower than their counterparts without jet injection shown in Table 1. The decrease of SF$_6$ leakage along the lower row (P1, P2 and P3) is particularly noticeable—the order of magnitude is $\sim 10^{-2}$ to $10^{-3}$ p.p.m. for the case without jet injection and is $\sim 10^{-2}$ to $10^{-3}$ p.p.m. for the case with jet injection. The leakage levels along the upper row (P4, P5 and P6) are also decreased, although the extent of decrease is not as large as that of the upper row.

Comparing the data of Table 2 for a fixed characteristic flow mode, one can see that operating the hood in the under-blow, transition or over-blow characteristic flow regimes in general would not cause drastic drop of the leakage by increasing the face velocity $V_o$ from 0.4 to 0.5 m s$^{-1}.$ However, if the cross-comparison is made among the three characteristic modes, it is apparent that operating the cupboard at the transition mode would lead to a most satisfactory containment performance—all the average leakage levels are just within few p.p.b. only and the upper and lower rows have similar low-leakage levels. While in the under-blow and over-blow modes, the leakage levels are generally higher than those of the transition mode. Besides, the leakage levels of the lower row are higher than those of the upper row. In particular, the leakage levels of the over-blow mode present the highest values among the three characteristic flow modes.

Performance verification of commercial fume cupboards

The commercial cupboards, which are denoted as CAV #1 and CAV #2, are used to examine the performance of the doorsill jet injection technique. Both the two fume cupboards have been fine-tuned by the manufacturer to their best situations. The test results for the fume cupboard without the jet injection are shown in Table 3. The leakage levels of CAV #1, although are much lower than those listed in the Table I for the experimental prototype fume cupboard, still present appreciable and unacceptable leakage values. The cupboard CAV #2 has similar leakage levels to those of the experimental prototype fume cupboard. By providing the doorsill jet injection to CAV #1 and CAV #2 and operating the flow parameters in the transition regime, the average leakage levels are drastically lowered to $\sim 10^{-2}$ to $10^{-3}$ p.p.m., as shown in Table 4. The practical application of the doorsill jet injection technique to the
commercial fume cupboards seems to be effective in reducing the contaminant leakage.

**CONCLUSIONS AND RECOMMENDATIONS**

The commonly used chemical fume cupboard presents prominent weakness around the areas near the doorsill and side poles. The high leakage risk around these regions is induced by the inappropriate aerodynamic design such as the sharp corners of the doorsill and the side poles which could induce flow separation and recirculation. Flow separation and accompanied recirculation occurring around these high-risk regions are the primary causes which lead to turbulent diffusion and thus the contaminant spillage. The doorsill jet injection technique developed and examined in this study shows that the in-cupboard contaminant could be effectively isolated from the outer environment by the jet issued behind the doorsill. With the doorsill jet injection, the visualized flow patterns show the very superior characteristics of contaminant isolation. The tracer gas tests show lower leakage than those of the cupboard without doorsill jet injection. The flow features can be categorized into three characteristic flow modes: under-blow, transition and over-blow, depending on the regimes in the domain of the face and jet velocities. Operating the cupboard at the under-blow (very low jet velocity) would induce little diffusion of jet fluids into the recirculation bubble on the doorsill. Pushing the jet velocity up to the over-blow regime would induce strong turbulence diffusion at higher...
attitudes where the jet breaks up. The transition mode appears to be the most effective operating regime that the contaminant isolation works properly and cross-flow diffusion is inappreciable. The tracer gas tests support the results of flow visualization. Although the static test results using the EN 14175 protocol present effectiveness of reducing the contaminant leakage by the doorsill jet injection, it is recommended that the dynamic tests, including the draft and sash movement tests, should be performed in order to examine the practical applicability of this technology.

**FUNDING**

Ministry of Education of Taiwan, Republic of China (0940081791).

**REFERENCES**


Table 4. Mean and peak values of SF6 concentrations of commercial cupboard with doorsill jet injection

<table>
<thead>
<tr>
<th>Grid position</th>
<th>( V_o = 0.4 \text{ m s}^{-1} ), ( V_b = 3.2 \text{ m s}^{-1} )</th>
<th>( V_o = 0.5 \text{ m s}^{-1} ), ( V_b = 3.2 \text{ m s}^{-1} )</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>( C_{ave} ) (p.p.m.)</td>
<td>( C_{max} ) (p.p.m.)</td>
</tr>
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<td>CAV #1</td>
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<tr>
<td>P1</td>
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d = 10 mm, \( H = 500 \) mm.