Flow and Containment Characteristics of a Sash-less, Variable-Height Inclined Air-Curtain Fume Hood

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To increase containment efficiency and reduce energy consumption, a sash-less, variable-height inclined air-curtain fume hood (sIAC hood) was developed and tested by a laser-assisted flow visualization technique and tracer-gas detection method. This novel design requires neither sash nor baffle. The sIAC hood employed the inclined push-pull air-curtain technique and two deflection plates installed on the side walls of the hood to induce a tetra-vortex flow structure. The results of flow visualization showed that the slot for suction flow, offset from the slot for the up-blowing jet, caused the air curtain to incline towards the rear wall, thus enhancing the robustness of the tetra-vortex flow structure. Such a flow structure could reduce the influence of draught and human walk-by across the hood face. The containment around the central area of the hood was isolated by the inclined push-pull air curtain. The pollutants carried by the reverse flow induced by the flow separation were guided by the deflection plates from the side walls towards the rear, thus contributing to the formation of the tetra-vortex flow structure. The up/down movable ceiling positioned the suction slot close to the device’s pollutant emission opening, but left room (less than 50 cm) for unrestricted hand movement. Testing was carried out based on the methodology described in EN14175. The results of a static test showed that small face velocities of 0.25 and 0.16 m s\textsuperscript{-1} were enough to obtain nearly null leakage levels for low and tall pollutant sources. The results of a traversing plate test showed that the face velocity, 0.32 m s\textsuperscript{-1}, would cause negligibly small leakage levels. The sIAC hood could obtain significantly higher containment efficiency than a conventional hood by operating at a face velocity significantly lower than that of conventional hoods.

Keywords: flow visualization; fume hood; inclined air curtain; sash height; tracer-gas test

INTRODUCTION

Fume hoods are designed to contain and remove harmful contaminants in workplaces and are indispensable for employees in laboratories and factories. Conventional fume hoods (or fume cupboards) consist of an enclosure with a canopy top, a baffle, an adjustable front opening, and an exhaust system to draw contaminants from the fume hood. The canopy top is fixed 1.0–1.3 m above the work surface. The baffle is designed to regulate the direction of the suction flow and to proportionately distribute the suction flow rates through the canopy top and the baffle slots. The open front is usually installed with a movable sash that protects the user while allowing for experiment manipulation. The exhaust system is connected to the fume hood, which draws room air through the hood’s sash opening and expels the contaminated air from the laboratory. The performance and characteristics of conventional fume hoods have been widely studied, e.g. First (2003),...
Tseng et al. (2007a, 2007b), and Ahn et al. (2008). The performance of conventional fume hoods was found to be determined by many factors, such as suction flow rate, face velocity, geometry of the work chamber, and baffle design. When operating in a static environment, conventional fume hoods may result in containment leakage due to boundary-layer separation and flow recirculation around the sash opening. Under dynamic situations (e.g. human walk-by, cross drafts, and sash movement) conventional fume hoods may result in some containment leakage. The general configurations and operating principles of conventional fume hoods have not changed significantly over the past few decades.

Face velocity is the most frequently emphasized parameter in specifying hood performance. However, previous studies have suggested that maintaining a specific face velocity does not assure the containment performance of fume hoods (Ivanov et al., 1989; Fletcher and Johnson, 1992a; Fletcher and Johnson, 1992b; Volin et al., 1998; Maupins and Hitchings, 1998). Boundary-layer separation and flow recirculation around a fume hood’s doorsill and side posts are the main potentials sources of hazard for contaminant leakage (Guffey et al., 2001; Tseng et al., 2006). In addition, the recirculation flow formed in front of the operator’s chest as the flow drawn into the sash opening flows across the operator’s body (Flynn and Ljungqvist, 1995). However, the presence of the sash both reduces operator exposure and affords splash protection. Increasing the face velocity increases the intensity of flow separation and recirculation. As the face velocity is increased beyond certain critical values, turbulent dispersions, induced by the increased intensity of boundary-layer separation and flow recirculation, balance or overwhelm the effect of suction force, thus limiting containment efficiency and potentially increasing hood containment leakage. A rule of thumb for designing the suction flow rate of conventional fume hoods is to keep the face velocity within the range of 0.3–0.7 m s\(^{-1}\), with manufacturers usually taking the average value, 0.5 m s\(^{-1}\), as a design reference. Techniques developed to improve the inherent deficiencies of conventional fume hoods include a by-pass design inside the hood above the sash, the provision of auxiliary air near the hood face just above the worker, a doorsill airfoil installation, doorsill compensation air, variable air volume operation (Joao et al., 1998; Ekberg and Melin, 2000), an adaptive back baffle, vortex-isolation jets, and doorsill injection (Tseng et al., 2008). While these techniques do improve containment efficiency, the inherent global and local recirculation flow structures induced by the boundary-layer separation or the blockage effect will still inevitably induce more or less turbulent dispersion of the contaminants.

Huang et al. (2007a, 2007b) developed a new type of fume hood, known as an air-curtain fume hood (AC hood), using the push-pull air curtain technique (Huang et al., 2005). This hood consists of three parts—a doubled-layered sash structured to supply a plane push jet, a suction slot installed behind the doorsill to exhaust contaminants, and a cabinet with screens or grids installed on the top of the hood for air flow compensation. No baffle is required, and the doorsill and side posts do not need a streamlined configuration to meet the aerodynamic requirements. Essentially, it is an empty cabinet fitted with a push jet, suction slot, and hood ceiling. The push jet and the suction flow were designed to create a push-pull air curtain (Huang et al., 2005) in the sash plane to aerodynamically separate the interior of the cabinet from the outside atmosphere. The AC hood was evaluated using standard tracer-gas concentration methods: EN 14175-3:2003 (2003) and ANSI/ASHRAE 110–1995 (American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc, 1995). Static and dynamic test results showed almost zero leakage levels. However, the double-layered sash structure caused practical difficulties in terms of manufacturing a hood wider than 180 cm. Another difficulty was under the situation of tall pollutant-generation devices. When a tall contaminant-generating device was placed in the cabinet, a larger suction flow rate was required to prevent containment leakage, because the contaminant emission source was further from the suction slot installed behind the doorsill.

To overcome the abovementioned deficiencies of the conventional fume hood and the AC hood, this study develops and examines a novel fume hood, known as a sash-less, variable-height inclined air-curtain hood (sIAC hood). The sIAC hood was developed to (1) reduce turbulent dispersions induced by boundary-layer separation and flow recirculation, (2) adapt for use with both low and tall contaminant emissions, and (3)
maintain low leakage and energy consumption levels similar to those of the AC hood. The flow behaviour was studied using the laser-light sheet flow visualization method. The tracer-gas test was performed based on the test method described in EN14175 to investigate the proposed hood’s leakage levels.

MATERIALS AND METHODS

Development of sIAC hood

Fig. 1 shows a schematic diagram of the configurations and primary dimensions of the sIAC hood. The hood comprises a rectangular cabinet with a back wall, two side walls, a ceiling box, and a work surface. The width from the left inner side wall to the right inner side wall is 150 cm. The ceiling is fitted with a rectangular box that can slide up and down along vertically aligned rails and be fixed at certain heights. A narrow suction slot (120 cm in length x 2 cm in width) is installed on the bottom face of the movable ceiling box to exhaust the contaminants. The ceiling box can be fixed at a height such that its bottom face is close to the pollutant emission opening but still allows room for convenient operation. This design was adopted because the upward flow velocity tends to rapidly decrease as the distance from the suction opening increases (Dalla Valle, 1945). Placing the suction opening close to the pollutant emission opening helps to increase the capture efficiency and save energy. The average suction velocity at the suction slot induced by the exhaust blower is denoted as $V_s$. The height from the bottom of the ceiling box to the work surface is denoted as $H$.

Fig. 1. Configurations of sIAC hood.
and could be varied from 0 to 130 cm. The suction flow rate is measured using a Venturi flow meter equipped with a high precision pressure transducer that was calibrated in-house at regular frequent intervals in time. The accuracy of the suction flow rate measurement is within the range of 1.5% of the converted reading.

A long, slim device composed of three internal cross-flow fans is installed near the front edge of the work surface to supply a slot jet. The length and width of the jet exit are 90 and 2 cm, respectively. The jet velocity at the slot exit is fixed at \( V_b = 1 \) m s\(^{-1}\). The jet issues vertically, up through the slot of the device containing the cross-flow fans. Through this arrangement, an inclined air curtain is expected to extend from the jet exit to the suction slot on the bottom face of the ceiling box. Huang et al. (2005) developed a ‘push-pull air curtain’ formed by an in-line arrangement of a slot for the blowing jet and a slot for suction flow. With properly adjusted physical operation parameters (e.g. suction and jet velocities) and geometric designs (e.g. widths of suction slot and jet exit, distance between the suction slot and the jet exit), such an arrangement can create a very robust ‘two-dimensional’ stream that can effectively isolate the spillage of pollutants. Investigators have validated the performance and properties of the push-pull air curtain, with extremely low levels of pollutant leakage resulting from a large open area equipped with a fume hood and biological safety cabinet installed with push-pull air curtains (Huang and Chou 2009; Huang et al., 2005, 2007a, 2007b, 2009). However, for the current study, the in-line arrangement of a slot for a blowing jet and a slot for suction flow is inconvenient. Arranging the push-pull air curtain as an ‘inclined’ type (i.e. a transverse offset exists between the slots of the jet and the suction flow) is more practical. The jet velocity was measured by a calibrated fine-wire hot-wire anemometer. In practical use, the long, slim device used to provide the up-blowing jet would cause a certain degree of inconvenience in operation. However, the device can be imbedded under the work surface so that the jet issues from a slot opening in the work surface.

Guide vanes of a quarter circular arc (with a radius of 10 cm) are installed on the front edges of the side posts and the work surface to reduce the effect of flow separation (Tseng et al., 2006), which can cause serious contaminant dispersion.

**Laser-light sheet flow visualization**

This study used the Mie scattering technique (Li and Tankin, 1987) to visualize the flow patterns with a wavelength of 532 nm. Using a set of optics, the laser beam was bundled in a planar laser sheet with a thickness of about 0.5 mm. Mineral oil mist was continuously seeded into the air curtain or into the local area of the sIAC hood via a homemade smoke generator to scatter the laser light for flow visualization, thus ensuring the flow field was not significantly affected. The diameter of the oil-mist particles, measured by a Malvern 2600C particle analyzer, was 1.7 ± 0.2 μm and they had a density of 0.821 g ml\(^{-1}\). The relaxation time was estimated at less than 7.7 × 10\(^{-5}\) s and the Stokes number was in the order of 10\(^{-6}\). Ignoring the effect of turbulent diffusion, the seeding particles could properly follow the flow up to at least 10 kHz (Flagan and Seinfeld, 1988). Images of the flow visualization were recorded by a charge-coupled device (CCD) camera. The CCD camera could record images at 30 or 60 fps, and the exposure time could be varied from 0.1 ms to 0.5 s.

**Tracer gas test**

Hood performance was assessed using methodologies based on the static and robustness (traversing plate) test methods described in EN14175-3 Fume cupboards–Part 3: Type test methods (European Committee for Standardization, 2003).

For the static test, the sampling grid, which was used to measure the local area-averaged leakage concentrations, was composed of nine stainless steel sampling probes, as shown in Fig. 2a. Each sampling probe had a diameter of 1.0 ± 0.1 cm, and a length of 15 cm, and each was fitted with a 3-cm inner diameter funnel-shape effuser at the inlet. The suction velocity of the effuser at the inlet was 3 cm s\(^{-1}\). The measurement locations for \( H = 50 \) and 100 cm are shown respectively in Figs. 2c and d. The inlet plane of the sampling grid was placed in the plane of the hood face (i.e. the \( x-z \) plane at \( y = -14 \) cm). The tracer gas was 10% SF\(_6\) in N\(_2\). The tracer gas ejector was a hollow cylinder with a diffusion plate made of sintered metal installed in the ejector. The diameter and length of the ejector cylinder were 1.25 and 2.5 cm,
respectively. A pressure gauge, a needle valve and a rotameter calibrated with the SF$_6$/N$_2$ mixture were attached to a piping system to control the flow rate of SF$_6$ at 2 L min$^{-1}$, such that the exit velocity of the ejector was about 27 cm s$^{-1}$. Each measurement run lasted 6 min.

For the traversing plate test, a flat rectangular plate 190 cm high, 40 cm wide and 2 cm thick was mounted on an electric motor-controlled traversing mechanism, as shown in Fig. 3. The plate was installed upright and perpendicular to the front plane of the IAC hood, 20 cm above the floor and 40 cm from the hood face. The plate was driven forwards from the right to the left of the hood at a constant speed of 1.0 m s$^{-1}$ until it was 60 cm to the left of the hood’s left side post, at which point it was immediately driven backwards across the front face of the hood to 60 cm to the right of the right side post. A total of six traverses of the plate were done, with a separation time of 30 s between two round-trip traverses. This test can be thought of as a person walking past a fume cupboard, although it does not represent a person. Fig. 4 shows the deployments of the ejectors and sampling probes for the $H = 50$ cm experiment. Nine gas ejectors were positioned inside the

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**Fig. 2.** Allocation of sampling grid for static test. (a) grid of sampling probes, (b) deployment of sampling grid at $H = 50$ cm, (c) deployment of sampling grid at $H = 100$ cm.
Flow and containment characteristics of an air-curtain fume hood

The nine ejectors were fixed in the non-uniform grids formed by the intersections of several horizontal and vertical lines. The upper, middle and lower rows of the ejector-grid were positioned at heights of 65, 25, and 10 cm from the hood’s work surface. The total release rate of the mixture of air and nitrogen was 4.5 L min$^{-1}$, so that the velocity at the exits of the ejectors was about 0.07 m s$^{-1}$. Twenty-five sampling probes (each with an inner diameter of 1 cm and a length of 10 cm) were positioned at the grid on a rectangular area in the measurement plane, as shown in Fig. 4a. The inlets of the sampling probes were positioned on the measurement plane, 5 cm from the hood’s opening plane. These sampling probes were connected to the inlets of a 3534 cm$^3$ mixing chamber by Teflon tubes of equal length. The suction velocity at the inlet of each sampling probe was approximately 3 cm s$^{-1}$.

A Miran SaphIRe™ Infrared Analyzer was used to measure the leakage concentration of the sulphur hexafluoride gas. The instrument was a single beam infrared spectrometer that used a pyroelectric lithium tantalite substrate as the detector. The resolution could be set at either 0.01 or 0.001 ppm for display. The instrument was calibrated in the test facility over four ranges: 0–1, 1–4, 4–24, and >24 ppm. The calibration curves were used to calculate the concentration values. Calculated values lower than 0.001 ppm were regarded as ‘undetectable’. The internal sampling rate of the detector was 20 readings per second. Values in this study were averaged over 10 s.

RESULTS AND DISCUSSION

Flow patterns at $H = 50$ cm

If the pollutant-generating device placed in the hood for operation is not tall, the ceiling box is lowered and fixed at a low height above the device. Preliminary experiments showed that containment efficiency could be improved if the distance between the bottom of the ceiling box and the pollutant emission opening at the top of the device was less than 50 cm. Fig. 5 shows an oblique view of the flow pattern in the horizontal plane of the sIAC hood at $H = 50$ cm. The smoke was released from the work surface via two tubes. For the visualization, the horizontal plane was at a height of

Fig. 3. Traversing mechanism and its deployment for traversing plate test. (a) side view, (b) top view.
Fig. 4. Deployment of sampling probes and gas release device for traversing plate test. $H = 50\text{ cm}$.

Fig. 5. Smoke images in horizontal plane at $z = 20\text{ cm}$ of sIAC hood. (a) whole view, (b) around left side wall. $H = 50\text{ cm}$, $V_s = 14\left(V_{\text{face}} = 0.44\text{ m s}^{-1}\right)\text{ m s}^{-1}$.
$z = 20 \text{ cm}$. The thick dotted lines denote the interface between the walls of the hood. The thin dotted lines represent the contours of the deflection plates, as well as the device that supplies the up-blowing plane jet. Four counter-rotating vortices appear in the horizontal plane. The video recordings from the CCD camera show clear consecutive images of rotation motion. The arrowheads indicate the visual rotation directions of the vortices. Two smaller vortices are located near the rear corners of the hood, and two larger vortices are located around the central area, with neighboring vortices rotating in opposite directions. The flow behind the plate can be rendered visible by replacing the deflection plate with a transparent acrylic plate. Fig. 5b shows an enlargement of the flow image around the left side wall with the installation of this transparent left deflection plate. It can be seen that the flow near the rear left corner of the hood goes outward along the left side wall, reaches the rear surface of the left deflection plate, reverses along the rear surface of the left deflection plate, and forms a counter-clockwise rotating vortex located around the rear left corner of the hood. To satisfy the flow topology (Perry and Fairlie, 1974; Hunt et al., 1978), a vortex rotating in a clockwise direction is induced next to the left rear corner vortex. Near the central area of the hood the flow between the two larger vortices moves outward due to the entrainment effect of the up-blowing jet. The combined effect induced by the entrainment of the up-blowing jet and the guidance of the deflection plate causes the formation of a tetra-vortex flow structure. By carefully adjusting the suction and jet velocities as well as the geometries (i.e. sizes, locations, and inclination angles) of the deflection plates, suction slot and jet slot, the flow field can be optimized so that the four vortices are enclosed in the cabinet behind the up-blowing jet and the deflection plates, which are located far from the hood face.

If the deflection plate is removed, the flow pattern in the horizontal plane becomes that shown in Fig. 6a. Flow separation occurs around the interface between the left guide vane and the left side wall so that the flow near the left side wall goes outward, reaches the separation point, and turns around to go inward with the flow drawn into the hood. The counter-rotating vortices do not appear as coherent as those shown in Fig. 5b. The rotation rates are also not as fast as those shown in Fig. 5b. The smoke in the region of the separation point sometimes disperses out of the hood due to the unsteady characteristics of the separated boundary-layer flow. In addition, since the separation point is located near the hood face, the smoke is very sensitive to the influence of environmental drafts. The flow around the central area is isolated by the up-blowing jet. If the deflection plates and the up-blowing jet are removed, the flow pattern becomes chaotic, as shown in Fig. 6b. Boundary-layer separation still appears around the left side wall near the hood face. However, no coherent tetra-vortex flow structure is observed either in the photo or in the video. Instead, the turbulent flow fills the entire hood and spreads out to the edge of the hood face. In this situation, the smoke frequently disperses out of the hood face into the environment from the areas near the side walls and the central area.

Fig. 7 shows an oblique view of the smoke images of the inclined push-pull air curtain across the vertical symmetry plane. The smoke is released through the inlet of the cross-flow fans so that the smoke particles delineate the trajectory of the slot jet. As shown in Fig. 7a, at a low suction velocity, $V_s = 6 \text{ m s}^{-1}$ (corresponding to a face velocity $V_{face} = 0.19 \text{ m s}^{-1}$), the air curtain presents convexly towards the hood face. As shown in Fig. 7b, the air curtain straightens as the suction velocity is increased to $V_s = 8 \text{ m s}^{-1}$ ($V_{face} = 0.25 \text{ m s}^{-1}$). As shown in Fig. 7c, at a higher suction velocity, $V_s = 10 \text{ m s}^{-1}$ ($V_{face} = 0.32 \text{ m s}^{-1}$), the air curtain presents concavely in the lower part and concavely in the upper part. This type of air curtain is denoted as a ‘transition mode’. As shown in Fig. 7d at a suction velocity, $V_s = 12 \text{ m s}^{-1}$ ($V_{face} = 0.38 \text{ m s}^{-1}$), the air curtain presents concavely towards the rear wall. Further increasing the suction velocity beyond $12 \text{ m s}^{-1}$ (or a face velocity beyond $0.38 \text{ m s}^{-1}$) accentuates the concave appearance of the air curtain and increases its coherence. Fig. 8 shows images of the smoke released inside the hood, with operating conditions corresponding to those in Fig. 7. As indicated by the arrowheads, the outer boundaries of the containment in the hood emulate the appearance of characteristic air-curtain flow modes. Obviously, the hood containment in Fig. 8 is isolated by the air curtain in each of the characteristic flow modes shown in Fig. 7. Intuitively, operating the hood in the ‘concave mode’ would cause the contaminant to be enclosed in the area closer to the rear wall than would be the case if operated in the ‘convex mode’. Considering the effects of human walk-by, cross drafts, and recirculation bubbles in the wake of the operator’s chest, operating the air curtain in ‘concave mode’ would be safer than operating in ‘convex mode’.
For comparison, Fig. 9 shows an oblique view of the smoke images across the vertical symmetry plane with no up-blowing jet. Even though a guide vane of a quarter-circular arc is installed at the front edge of the work surface, the flow still separates around the interface between the guide vane and the work surface. From the pictures, it is difficult to judge where exactly the boundary layer separates from the solid work surface. However, according to fundamental research on flows past a circular cylinder (Huang et al., 2006), the separation location for the low speed flow would be located about 77° from the leading edge of a circular cylinder. This means that the flow separates from the surface of the quarter-circular arc before it reaches the interface between the guide vane and the work surface. Separation of the boundary layer is followed by a reverse flow, and dispersion of the contaminant through the separated boundary layer towards the atmosphere becomes regular. By installing the up-blowing jet downstream of the separation point, the contaminant can be isolated in the hood and kept away from the hood face, as shown in Fig. 8.

Fig. 6. Smoke images in horizontal plane at \( z = 20 \) cm around left side wall. (a) sIAC hood without deflection plate, (b) sIAC hood without deflection plate and up-blowing jet. \( H = 50 \) cm, \( V_s = 14 (V_{\text{face}} = 0.44) \) m s\(^{-1}\).

Fig. 10 shows an oblique view of the consecutive smoke images across the vertical symmetry plane under the influence of the moving plate. The smoke is released inside the hood from the work surface. Figs. 10a–d represent the time evolution process of the smoke in the sIAC hood. Figs. 10e–h represent what occurs when the up-blowing jet is removed. At a suction velocity \( V_s = 10 \) m s\(^{-1}\), the flat plate (Fig. 3) at a distance 40 cm from the hood face, sweeps across the hood face at a velocity of 1 m s\(^{-1}\). With the up-blowing jet, as shown in Figs. 10a–d, the smoke in the hood fluctuates a little after the plate sweeps across, but no trace of smoke leakage out of the hood face is observed. As shown in Figs. 10e–h, when the up-blowing jet is removed the smoke disperses out of the hood face after the flat plate sweeps across the hood.
Flow and containment characteristics of an air-curtain fume hood

Since the separation point is located near the hood face, the induced reverse flow is very susceptible to environmental disturbances. After the flat plate sweeps across the hood face, the wake induces disturbances of convective current and pressure. The contaminant accumulated around the hood face thus disperses outwards to the environment.

Leakage concentrations of tracer gas at $H = 50$ cm

**Fig. 11** shows the static test results of SF$_6$ leakage concentration in the left-half plane (P1, P2, P5, and P6 in **Fig. 2b**) of the hood face. The suction velocity was $V_s = 6$ m s$^{-1}$ ($V_{face} = 0.19$ m s$^{-1}$). All measured instantaneous SF$_6$ concentrations fluctuated within a very small range of 0 to 0.003 ppm. For the upper row, at locations P1 and P2, the measured time-averaged SF$_6$ leakage concentrations were non-detectable ($C_{ave} < 0.001$ ppm). The maximum SF$_6$ leakage concentrations were only $C_{max} = 0.002$ ppm. For the lower row, at locations P5 and P6, the time-averaged SF$_6$ leakage concentrations were $C_{ave} = 0.001$ ppm. The maximum SF$_6$ leakage concentrations were only 0.003 ppm. All measurement results showed negligibly small leakage levels. When we increased the suction velocity $V_s$ to greater than or equal to 8 m s$^{-1}$ ($V_{face} \geq 0.25$ m s$^{-1}$), the mean leakages measured at all locations were almost null values, as shown in **Table 1**. This presents a considerable improvement over the performance behavior of the conventional hood. For the conventional fume hood, increasing the face velocity beyond a certain critical value usually only increases noise and energy consumption without improving containment performance because of the intensification of the boundary-layer separation and recirculation bubble (Tseng *et al.*, 2006). **Table 2** shows comparisons of the static test results between the sIAC hood and a conventional hood. The sIAC hood has a width of 150 cm and a ceiling-box height of 50 cm, and is operated at a face velocity of $V_{face} = 0.19$ m s$^{-1}$. The width of the conventional hood is 120 cm, with a sash height of 50 cm, and is operated at a face velocity of $V_{face} = 0.50$ m s$^{-1}$. The leakage concentration levels of the conventional hood detected in the upper row are not large, ranging from 0.021 to 0.081 ppm. The corresponding leakage levels of the sIAC hood in

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**Fig. 7.** Characteristic modes of inclined air curtain of sIAC hood. Smoke released from inlet of up-blowing jet. ($V_s, V_{face}$ = (a) (6, 0.19) m s$^{-1}$, (b) (8, 0.25) m s$^{-1}$, (c) (10, 0.32) m s$^{-1}$, (d) (12, 0.38) m s$^{-1}$, $H = 50$ cm.)
the upper row all fall below 0.002 ppm and are markedly smaller than those of the conventional hood. The leakage concentration levels of the conventional hood, detected in the lower row, are significantly large—from 23.963 to 30.534 ppm, while those of the sIAC hood in the lower row are almost zero—from non-detectable to 0.001 ppm. For the static test, the sIAC hood uses a face velocity of only 0.19 m s$^{-1}$ and achieves a negligibly small leakage level, whereas the conventional hood uses a face velocity of 0.50 m s$^{-1}$ and presents a significantly larger leakage level. The limit mean value for static test of fume cupboard set by France (AFNOR NF Standard X15-206, 2005) is also listed in Table 2 for comparison. The limit mean value available from France is 0.1 ppm. The maximum leakage value of the sIAC hood is 0.002 ppm, which is detected at the location P4. The maximum leakage value of the sIAC hood is far below the limit mean value set by France.

Fig. 12 shows the time histories of SF$_6$ leakage concentrations in the traversing plate test. As shown in Fig. 12a, at $V_s = 6$ m s$^{-1}$ ($V_{\text{face}} = 0.19$ m s$^{-1}$), the leakage level fluctuates drastically between approximately zero and 0.5 ppm. The average leakage value is $C_{\text{ave}} = 0.259$ ppm and the maximum value is $C_{\text{max}} = 0.465$ ppm. According to the suggestion of BG Chemie (2006), the German upper limits for the average and maximum concentration values using the EN14175-3 method are 0.65 and 3.25 ppm, respectively; currently, no other European Union country has specified pass/fail criteria. The leakage levels of the sIAC hood operated at a very low face velocity, $V_{\text{face}} = 0.19$ m s$^{-1}$, are far below these suggested upper limits. As shown in Figs. 12b–d, at a suction velocity greater than 6 m s$^{-1}$ ($V_{\text{face}} = 0.19$ m s$^{-1}$), the average and maximum leakages obtained in the traversing plate test were drastically reduced to very low values. In particular, as shown in Fig. 12d, at a suction velocity of $V_s = 12$ m s$^{-1}$ ($V_{\text{face}} = 0.38$ m s$^{-1}$), the average leakage value becomes negligibly small—only 0.003 ppm—and the maximum value is only 0.012 ppm. These small average and maximum leakage levels are comparable to those of the air-curtain fume hood (AC hood) reported by Huang et al. (2007a) at similar face velocities.

Table 3 compares the current results of the traversing plate tests on the sIAC hood to those of a conventional hood (Tseng et al., 2007a). This
Flow and containment characteristics of an air-curtain fume hood

conventional hood with a sash opening width of 120 cm operated at $V_{\text{face}} = 0.50$ m s$^{-1}$ presented an average leakage value of 1.230 ppm, which far exceeds the German limit value of 0.65 ppm. In contrast, the sIAC hood with a hood face width of 150 cm, even operating at a low face velocity of 0.19 m s$^{-1}$, still presents an average leakage level drastically smaller than that of a conventional hood. Operating at nearly the same face velocity, the leakage level of a conventional fume hood is almost 400 times that of the sIAC hood.

The quantitative measurement results of the sIAC hood, shown in Figs. 11 and 12 as well as Tables 1–3, are well correlated with the qualitative flow visualizations shown in Figs. 5, 6, 8, and 10. The SF$_6$ measurement results of the conventional fume hood (cited from Tseng et al. (2006, 2007a) and listed in Table 2) are well correlated with the flow visualization results in Fig. 6, indicating that the area most likely to leak is around the doorsill.

Flow patterns at $H = 100$ cm

If the pollutant-generating device placed in the hood is tall, the ceiling box is raised and fixed at a high altitude—leaving a space of less than 50 cm between the bottom of the ceiling box and the top of the device for operational convenience. For instance, if the device height is 50 cm, the ceiling height can be adjusted to an altitude of 50 cm $< H < 100$ cm; if the device height is 80 cm, the ceiling height can be adjusted to an altitude of 80 cm $< H < 130$ cm. Our pre-study tests showed that the sIAC hood maintained high containment performance with varying ceiling box altitude. The proposed technique could also be applied to the design of walk-in cabinet, and we are planning the further development of this device.

Fig. 13 shows the flow visualization results of the horizontal plane at $z = 40$ cm. Two open-top tanks were placed in the hood. The center of each open-top tank was located 30 cm from the rear wall and 30 cm from the side wall. The height and diameter of the tanks were 50 and 30 cm, respectively. The bottom of the ceiling box was adjusted to $H = 100$ cm, leaving a distance of 50 cm between the bottom of the ceiling box and the top of the tanks. Smoke was released from the tops of the tanks. As seen in Figs. 13a

Fig. 9. Smoke images in vertical symmetry plane of sIAC hood without up-blowing jet. Smoke released from work surface. ($V_s$, $V_{\text{face}}$) = (a) (6, 0.19) m s$^{-1}$, (b) (8, 0.25) m s$^{-1}$, (c) (10, 0.32) m s$^{-1}$, (d) (12, 0.38) m s$^{-1}$. $H = 50$ cm.
and b, at low suction velocities $V_s = 6$ and $8 \text{ m s}^{-1}$ ($V_{face} = 0.10$ and $0.13 \text{ m s}^{-1}$), a very small quantity of oil mist appears in the area between the two tanks. Under careful examination, this small quantity of oil mist travels downward after release from the top of the tank, spreads sideways, reaches the work surface, and may sometimes present a very small (almost invisible) dispersion across the hood face near the left or right corner. If the distance between the bottom

Fig. 10. Streak smoke images in vertical symmetry plane of sIAC hood subject influence of plate sweeping. (a–b) with up-blowing jet, (b) without up-blowing jet. $H = 50 \text{ cm}$, $V_s = 10 \text{ m s}^{-1}$ ($V_{face} = 0.32 \text{ m s}^{-1}$).
of the ceiling box and the top of the tank is lowered to 45 cm (i.e. \( H = 95 \text{ cm} \)) or less (not shown here), the downward-moving smoke disappears even at a low suction velocity of \( V_s = 6 \text{ m s}^{-1} \) \((V_{\text{face}} = 0.10 \text{ m s}^{-1})\). As shown in Figs. 13c and d, at larger suction velocities, \( V_s = 10 \text{ and } 12 \text{ m s}^{-1} \) \((V_{\text{face}} = 0.16 \text{ and } 0.19 \text{ m s}^{-1})\), \( H = 100 \text{ cm} \) is sufficient to ensure absolutely no trace of downward-moving smoke.

Fig. 14 shows an oblique view of the smoke images in the vertical plane across the right tank. At low suction velocities of \( V_s = 6 \text{ and } 8 \text{ m s}^{-1} \) \((V_{\text{face}} = 0.10 \text{ and } 0.13 \text{ m s}^{-1})\), the smoke released from the opening of the tank attaches to the rear wall and is drawn directly up into the suction slot. At a suction velocity of \( V_s = 10 \text{ m s}^{-1} \) \((V_{\text{face}} = 0.16 \text{ m s}^{-1})\), the density of the smoke attached to the rear wall is reduced. At a suction velocity of \( V_s = 12 \text{ m s}^{-1} \) \((V_{\text{face}} = 0.19 \text{ m s}^{-1})\), the smoke goes directly up into the suction slot without attaching to the rear wall at all.

**Leakage concentrations of tracer gas at \( H = 100 \text{ cm} \)**

Fig. 15 shows the history of tracer-gas measurement results of the sIAC at \( H = 100 \text{ cm} \). The grid locations P1, P3, and P5 were close to the left side of the hood face, as shown in Fig. 2c. At a low suction velocity of \( V_s = 6 \text{ (} V_{\text{face}} = 0.10 \text{ m s}^{-1})\), the leakage level of SF\(_6\) concentration around the upper corner is low \((C_{\text{ave}} = 0.004 \text{ ppm})\). As shown in Figs. 15b and c, in the middle section and at the lower corner, concentration peaks may appear at times, causing the average and maximum leakage SF\(_6\) concentrations to escalate. At the lower corner, P5, the maximum leakage is particularly significant. This measurement result corresponds
to the flow visualization such that, at low suction velocity, the smoke may drain out of the hood face around the corner area if \( H = 50 \) cm. If \( H \) is lowered by about 5 cm, the SF\(_6\) concentration (which is not shown here) around this area becomes almost non-detectable. No peaks appeared during the measurement period. As shown in Figs. 15d–f, at a suction velocity of \( V_s = 10 \) m s\(^{-1}\) (\( V_{\text{face}} = 0.16 \) m s\(^{-1}\)), all tracer gas measurements reveal non-detectable average concentrations of SF\(_6\), and the maximum SF\(_6\) concentrations become relatively small.

### CONCLUSIONS

The proposed sIAC hood employs an inclined, push-pull air-curtain technique to isolate potential containment leakage around the central area of the hood face and uses two deflection plates installed on the hood's side walls to induce a tetra-vortex flow structure and avoid flow-separation-induced containment leakage from the area around the side walls and the hood corners. This novel design can be used for either short or tall pollutant emission devices. The concept of a variable ceiling height was prompted by previous findings that the induced velocity going towards the suction opening decreases quickly and drastically as the distance from the suction opening increases. By adjusting the height of the ceiling box to be less than 50 cm from the pollutant emission device's opening, the leakage level of the contaminants in the hood can be drastically reduced to almost non-detectable values at a very low face velocity. Considering static conditions, respective face velocities of 0.25 and 0.16 m s\(^{-1}\) for low and tall release operations are more than sufficient to ensure almost non-detectable leakage. For comparison, static test results of a conventional hood showed that appreciable containment leakage was not unusual when using a face velocity of approximately 0.5 m s\(^{-1}\). For the traversing plate test, a face velocity at 0.32 m s\(^{-1}\) would cause negligibly small leakage in the proposed design.

### Table 1. SF\(_6\) leakage concentration of sIAC hood detected in static test, \( H = 50 \) cm.

<table>
<thead>
<tr>
<th>Sampling Grid Location</th>
<th>( V_{\text{face}} ) (m s(^{-1}))</th>
<th>( V_s ) (m s(^{-1}))</th>
<th>( C_{\text{ave}} ) (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.19</td>
<td>0.25</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
<td>P1</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>P2</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>P3</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>P4</td>
<td>0.002</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>P5</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>P6</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>P7</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>P8</td>
<td>0.001</td>
<td>&lt;0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

### Table 2. Comparisons of SF\(_6\) leakage concentrations between sIAC hood and conventional hood. Static test, \( H = 50 \) cm.

<table>
<thead>
<tr>
<th>Sampling Grid Location</th>
<th>sIAC Hood (Width of hood face: 150 cm)</th>
<th>Conventional Hood (Width of sash opening: 120 cm) (Tseng et al., 2006)</th>
<th>Limit value set by France (AFNOR NF Standard X15-206, 2005)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{\text{face}} = 0.19 ) m s(^{-1}) (( V_s = 6 ) m s(^{-1}))</td>
<td>( C_{\text{ave}} ) (ppm)</td>
<td>( C_{\text{ave}} ) (ppm)</td>
<td>( C_{\text{ave}} ) (ppm)</td>
</tr>
<tr>
<td>P1 (left, upper row)</td>
<td>&lt;0.001</td>
<td>0.021</td>
<td>0.1</td>
</tr>
<tr>
<td>P2</td>
<td>&lt;0.001</td>
<td>0.001</td>
<td>0.081</td>
</tr>
<tr>
<td>P3</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.081</td>
</tr>
<tr>
<td>P4 (right, upper row)</td>
<td>0.002</td>
<td>0.032</td>
<td>0.032</td>
</tr>
<tr>
<td>P5 (left, lower row)</td>
<td>0.001</td>
<td>23.963</td>
<td>23.963</td>
</tr>
<tr>
<td>P6</td>
<td>0.001</td>
<td>27.371</td>
<td>27.371</td>
</tr>
<tr>
<td>P7</td>
<td>&lt;0.001</td>
<td>30.534</td>
<td>30.534</td>
</tr>
</tbody>
</table>
At a face velocity of 0.19 m $s^{-1}$, the leakage level still remained drastically lower than the German threshold value. The proposed sIAC hood design results in significantly higher containment efficiency than conventional hoods while operating at a significantly lower face velocity. The sIAC hood exhibited levels of containment and energy efficiency very similar to those of the AC hood. The proposed design can be applied to the development of walk-in cabinets. However, the sIAC hood does not have a sash to act as a physical barrier to prevent splashes and, in extreme cases, to prevent the spread of hazardous materials.

Table 3. Comparisons of SF$_6$ leakage concentrations between sIAC hood and conventional hood. Traversing plate test, $H = 50$ cm.

<table>
<thead>
<tr>
<th>Hood Type</th>
<th>$V_{\text{face}}$ (m $s^{-1}$)</th>
<th>$V_{s}$ (m $s^{-1}$)</th>
<th>$C_{\text{ave}}$ (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>sIAC Hood (Width of hood face: 150 cm)</td>
<td>0.19</td>
<td>6</td>
<td>0.259</td>
</tr>
<tr>
<td></td>
<td>0.25</td>
<td>8</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>0.32</td>
<td>10</td>
<td>0.036</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>11</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>0.38</td>
<td>12</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>0.44</td>
<td>14</td>
<td>0.003</td>
</tr>
<tr>
<td>Conventional Hood (Width of sash opening: 120 cm) (Tseng et al., 2007a)</td>
<td>0.50</td>
<td></td>
<td>1.230</td>
</tr>
</tbody>
</table>
Fig. 13. Smoke images of horizontal plane at \( z = 40 \) cm. \((V_s, V_{face}) = (a) (6, 0.10) \text{ m s}^{-1}, (b) (8, 0.13) \text{ m s}^{-1}, (c) (10, 0.16) \text{ m s}^{-1}, (d) (12, 0.19) \text{ m s}^{-1}. H = 100\text{cm}.\) Oil mist released from top opening of tanks.

Fig. 14. Smoke images of vertical plane across right tank. \((V_s, V_{face}) = (a) (6, 0.10) \text{ m s}^{-1}, (b) (8, 0.13) \text{ m s}^{-1}, (c) (10, 0.16) \text{ m s}^{-1}, (d) (12, 0.19) \text{ m s}^{-1}. H = 100\text{cm}.\) Oil mist released from top opening of tanks.
offer some operator protection in the event of an explosion inside the fume cupboard.

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Available at http://www.waldner.co.uk/ports/10/downloads-uk/knowledge%20base/steffen%20springer%20[compatibility%20mode].pdf.


Tseng LC, Huang RF, Chen CC et al. (2007a) Effects of sash movement and walk-bys on aerodynamics and contaminant leakage of laboratory fume cupboards. Ind Health; 45: 199–208.

