Development and Characterization of an Inclined Air-Curtain (IAC) Fume Hood

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ABSTRACT

An inclined air-curtain (IAC) fume hood was developed and characterized using the laser-assisted smoke flow visualization technique and tracer-gas (sulphur hexafluoride) concentration detection method. The IAC fume hood features four innovative design elements: (i) an elongated suction slot installed at the hood roof with an offset towards the rear wall, (ii) an elongated up-blowing planar jet issued from the work surface near the hood inlet, (iii) two deflection plates installed at the left and right side walls, and (iv) a boundary-layer separation controller installed at the sash bottom. Baffles employed in conventional hoods were not used. The suction slot and the up-blowing planar jet formed a rearward-inclined push-pull air curtain. The deflection plates worked with the inclined air curtain to induce four rearward-inclined counter-rotating ‘tornados.’ The fumes generated in the hood were isolated behind the rearward-inclined air curtain, entrained by the low pressure within the vortical flows, moved up spirally, and finally exhausted through the suction slot. The risk of containment leakage due to the large recirculation vortex that usually exists behind the sash of conventional hoods was reduced by the boundary-layer separation controller. The results of the tracer-gas concentration detection method based on the EN-14175 method showed that the flow field created by the geometric configurations of the IAC hood presented characteristics of low leakage and high resistance to dynamic disturbances at low face velocities. The leakage levels measured by the static, sash movement, and walk-by tests were negligible at a face velocity of 0.26 m s⁻¹.

KEYWORDS: flow visualization; fume hood; IAC fume hood; inclined air curtain; tracer-gas test

INTRODUCTION

The fundamental configurations and operation principles of conventional laboratory fume hoods have not changed significantly over the past 60 years (First, 2003). The important elements of the fume hood structure generally include a box-like cabinet, an up/down movable front sash, and a baffle plate. These fundamental designs, if not carefully tuned by following aerodynamic principles, may induce leakage from containments. The primary problem encountered in conventional fume hoods, which has been widely discussed, is the weak correlation between face velocity and leakage levels. The following two paragraphs briefly discuss the phenomena and physical
mechanisms of the leakage problem of conventional fume hoods.

Because the air flow through the sash opening of a fume hood serves to contain the hazardous substances generated inside the hood, it has long been assumed that the effectiveness of a fume hood is strongly affected by the magnitude of the face velocity (Caplan and Knutson, 1982; Maupins and Hitchings, 1998). However, as indicated by First (2003) and Tseng et al. (2010), there is a weak correlation between the face velocity and leakage levels because many factors (such as boundary-layer separation, recirculating turbulent flow, wake in front of operator) may be responsible for leakage from the fume hood (Tseng et al. 2007, 2008). The boundary-layer separation is one area in a fume cupboard where one observes complex flow phenomena. When a flow passes over a structure with non-streamlined surfaces or edges, the induced adverse pressure may cause the flow near the wall to move upstream. The boundary layer originally attached to the surface of the structure thereby separates from the surface (Batchelor, 2000). Inlet guide vanes are common design elements used to reduce leakage occurring at the boundary-layer separation, as noted by Özdemir et al. (1993), and they are incorporated into many commercial products.

The baffle configuration is another important design parameter that has been examined by researchers in order to improve hood performance. Saunders (1984) reported that properly designed baffles can adjust the distribution of the inlet velocity through the sash opening and improve hood performance. Modifications to hood geometry and operation, including the auxiliary air, by-pass passage, streamlined doorsill, and variable air volume (VAV) methods have been proposed by manufacturers and researchers in order to improve containment efficiency. Nevertheless, the leakage levels of fume hoods may remain significant if the hood design is not improved. First (2003) established that the VAV method limits the face velocity of a fume hood within a range when the sash height is varied; however, the measured leakage levels were not reduced significantly.

An unconventional fume hood, namely, the air-curtain hood (AC hood), was proposed by Huang et al. (2007a, 2007b). This hood featured a blow-down plane jet issuing from the bottom of the sash and a suction slot behind the doorsill of the hood. A slightly concave push-pull air curtain was formed across the sash opening by such an arrangement. Huang et al. examined the AC hood by using the laser-assisted smoke flow visualization technique and tracer-gas concentration detection method, and found that the hood exhibits nearly zero leakage at moderate face velocities for both static and dynamic tests. For practical use, however, they identified the following issues with the AC hood. First, the double-layered sash structure might make it difficult to manufacture a hood wider than 1.8 m. Second, placing a tall device that generates high-temperature contaminants in the hood might require a high suction flow rate in order to prevent containment leakage.

Recently, Huang et al. (2013) developed a sashless inclined air-curtain fume hood (sIAC hood) in order to overcome the aforementioned drawbacks of the AC hood. The sIAC hood has a ceiling that can be adjusted up and down to fit the height of the pollutant-generation device such that the suction opening at the bottom face of the ceiling can be placed within a critical distance above the pollutant emission opening of the device. By such an arrangement, the sIAC hood exhibits negligible leakage levels with low energy consumption. However, according to Huang et al. (2013), because the sIAC hood does not have a sash, it is difficult for it to act as a physical barrier to prevent splashes and to offer some operator protection in the event of an explosion inside the fume cupboard. Moreover, the hood may not be airtight because of the movable ceiling, thereby increasing manufacturing difficulty.

To overcome the drawbacks of the sIAC hood, this study proposes an inclined air-curtain fume hood (IAC hood). The IAC hood has a fixed ceiling and an up/down movable sash, similar to those of a conventional fume hood. However, the IAC hood combines several aerodynamic elements unlike conventional hoods, including an elongated suction slot at the hood ceiling, two deflection plates attached to the hood side walls, a planar jet in the front part of the work surface, and a boundary-layer separation controller attached to the bottom of the sash. The laser-assisted smoke flow visualization technique and tracer-gas concentration detection method were employed to evaluate the flow characteristics and containment performance of the IAC hood, respectively. Tracer-gas leakage levels of the IAC hood were measured using an approach based on the methodology described in EN14175-3 Fume hood guidelines.
cupboards–Part 3: Type test methods (European Committee for Standardization, 2003). The leakage levels were measured in terms of sulphur hexafluoride (tracer gas) concentration. The measured concentration values were compared with the threshold value set by France (AFNOR NF Standard X15-206, 2005).

MATERIALS AND METHODS

IAC fume hood

Figure 1 shows a schematic diagram of the IAC hood. The hood consisted of a rectangular cabinet enclosed by a rear wall, two side walls, an air box, a work surface, and an up/down movable sash. The width (x direction), depth (y direction), and height (z direction) of the cabinet were 150, 75, and 100 cm, respectively. The sash height \( H \) was defined as the distance from the work surface to the bottom of the sash. By adjusting the sash height, the area of the front opening, which serves as an inlet for air, could be changed. The cabinet and sash were made from transparent acrylics for convenience of flow visualization, and they were mounted on a steel frame.

A flat rectangular plate (150 cm × 6 cm) was attached to the sash bottom at an angle of 30° from the horizontal, as shown in the inset of Fig. 1. This plate is called the boundary-layer separation controller, and its purpose will be explained later.

Two rectangular plates (15 cm × 100 cm), namely, deflection plates, were attached to the side walls of the hood, facing rearwards at an included angle of 45°. The leading edge of each deflection plate was placed on the side wall at 69 cm from the rear wall of the IAC fume hood. A slot opening (90 cm × 2 cm) was set up in the front part of the work surface to allow vertical generation of a planar jet. The planar jet was supplied by a cross-flow fan installed below the work surface. The velocity of the jet issuing from the slot was fixed at \( V_b = 1 \text{ m s}^{-1} \).

Guide vanes in the form of quarter-circle arcs (radius, 12 cm) were installed on the front edges of the side posts and the work surface. A suction slot (120 cm × 2 cm) was installed on the bottom face of an air box to exhaust the contaminants. The air and fumes were exhausted to the outside through the suction slot, air box, two circular outlets in the air box, and a piping system by the driving force of a blower.

The suction flow rate \( Q_s \) was measured using a Venturi flow meter and a calibrated pressure transducer. The average suction velocity \( V_s \) at the suction slot, induced by the exhaust blower, was calculated by dividing \( Q_s \) by the area of the suction slot. A Cartesian coordinate system (x-y-z) was originated at the centre of the front edge of the rectangular cabinet for reference. The flow rates used in this study were 8.6, 11.7, 14.4, and 17.1 m \( ^3 \) min\(^{-1} \). The face velocities corresponding to the previously mentioned flow rates were 0.19, 0.26, 0.32, 0.38, and 0.45 m s\(^{-1} \). The flow rates and face velocities were selected for the experiments so as to cover all three characteristic flow modes observed in our preliminary studies. These three characteristic flow modes were not identified previously, and they will be discussed later.

Laser-light sheet flow visualization

Mie scattering (Li and Tankin, 1987) was used to visualize the flow patterns. A portable laser that emitted a green light beam at a wavelength of 532 nm was used as the light source. The laser beam was expanded by a set of cylindrical optics to a triangular laser-light sheet around 0.5 mm thick. The laser-light sheet was aligned at some target planes in the hood to reveal images of smoke passing through the laser-light sheet. Mineral oil mists (diameter, 1.7 ± 0.2 μm) generated from a homemade smoke generator were continuously seeded into the target area of the hood to scatter the laser light for flow visualization. Images of the flow visualization were recorded by a charge-coupled device.
(CCD) camera that could record moving images at a frame rate of 60 fps. Video clips were recorded, and the instantaneous images presented in the paper were taken from streak pictures of the recorded video clips.

**Tracer-gas test**

Tracer-gas testing of the IAC hood was performed in accordance with the methodology described in EN14175-3 Fume cupboards–Part 3: Type test methods (European Committee for Standardization, 2003). The tracer gas was 10% sulphur hexafluoride (SF\(_6\)) in nitrogen (N\(_2\)). The sash height \(H\) was adjusted to 50 cm. The EN14175-3 method includes three tests: inner-plane test (i.e. static test), outer-plane test (i.e. sash movement test), and robustness test (i.e. simulated walk-by test). A MIRAN SapphIRe™ infrared analyzer was used to measure the leakage concentration of SF\(_6\). The accuracies of the instrument were ±10% and ±20% of reading for the ranges of 0–1 and 1–4 ppm, respectively. The instrument could display the measurement results at a resolution of either 0.01 or 0.001 ppm. It calculated the concentration values using the calibration curves installed in the instrument. The displayed values were obtained by rounding off the calculated values to the second or third place after the decimal point. Because the leakage levels of the IAC fume hood were lower than 0.01 ppm, we used a resolution 0.001 ppm for displaying the measurements. The internal sampling rate was 20 readings per second.

To conduct the inner-plane test, a sampling grid consisting of nine sampling probes, which were deployed over a square area of 20 cm × 20 cm, was used to measure the local area-averaged leakage concentrations. The sampling probes (diameter, 1 cm; length, 15 cm) were made from stainless steel. They were connected to the inlets of a mixing manifold by Teflon tubes of equal lengths. A detector probe was affixed to the outlet of the mixing manifold and connected to the MIRAN SapphIRe™ infrared analyzer. The nine-probe sampling grid was placed at the locations shown in Fig. 2a. The inlet plane of the sampling grid was aligned in the plane of the hood face (i.e. the plane of \(y = 0\)). The suction velocity at the probe inlet was adjusted to 10 cm s\(^{-1}\) by using a needle valve. Sampling for the probe-grid positions, as denoted by P1–P8 in Fig. 2a, was performed sequentially for 360 s at each grid position, while the tracer gas was released into the cabinet. The data for the initial 59 s were discarded. The tracer-gas ejector was a hollow cylinder (diameter, 1.25 cm; length, 2.5 cm). A diffusion plate made from sintered metal was installed in the ejector. The ejection flow rate of the SF\(_6)/\text{N}_2\) mixture was 2.1 l min\(^{-1}\), which was measured by a rotameter and controlled by a pressure regulator and a needle valve. The tracer-gas ejector was installed vertically inside the cabinet with its exit facing up. The centre point of the ejector exit was always placed in a plane 15 cm away from the sash plane and aligned with the centre probe of the sampling grid.

To conduct the outer-plane test, the experimental arrangement shown in Fig. 2b was used. Nine ejectors were simultaneously positioned inside the cabinet in a plane 20 cm away from the sash plane, and they were placed horizontally with the exits facing the sash plane so that the gases were ejected outwards. The diameter and length of the ejector were the same as those used in the inner-plane measurement. The release rate of the tracer-gas mixture was 4.5 l min\(^{-1}\) so that the velocity at the exits of the ejectors was around 7 cm s\(^{-1}\). A total of 20 sampling probes were positioned at the grids over a rectangular area in the measurement plane, as shown by the black dots in Fig. 2b. The inlets of the sampling probes were in a measurement plane 5 cm away from the sash plane. The 20 sampling probes (inner diameter, 1 cm) were connected to the inlets of a mixing chamber through Teflon tubes of equal length. The suction velocity at the inlets of the sampling probes was \(\sim 10\) cm s\(^{-1}\). The detector probe was inserted into the outlet of the mixing chamber. Sampling was performed for 780 s (13 min), and the data for the initial 59 s were discarded. The sash was initially opened to a height of \(H = 50\) cm. After 360 s (6 min), the sash was closed. After 600 s (10 min), the sash was reopened to a height of 50 cm.

For the robustness test, the deployments of the ejectors and sampling probes were identical to those in the outer-plane test (Fig. 2b). A flat rectangular plate, similar to that used by Huang et al. (2007a, 2007b) (190 cm × 40 cm × 2 cm), was mounted on a feedback-controlled motor-driven cart. The plate was installed upright and perpendicular to the sash plane, 20 cm above the floor and 40 cm from the farthest part of the sash plane. During the experiment, the plate was
driven forward and immediately backward across the face of the fume hood by the cart at a speed of 1.0 m s\(^{-1}\). Let one traverse denote a round-trip motion (i.e. forward and backward) of the sweeping plate. In total, six traverses were completed at an interval of 30 ± 2 s between traverses. The traverse of the plate was extended for 60 cm on each side beyond the width of the hood. Sampling was performed for 270 s. The data for the initial 59 s and the final 30 s were discarded.

RESULTS AND DISCUSSION

Flow patterns of IAC hood
Figure 3a shows the flow patterns in the right half of the horizontal plane \(z = 5\) cm when the narrow suction slot, deflection plates, and up-blowing jet of the IAC hood shown in Fig. 1 were functioning and operating at a face velocity 0.32 m s\(^{-1}\). Near the right rear corner, a clockwise-rotating vortex (denoted by \(N_1\)) is formed between the right deflection plate and the rear wall. The right deflection plate stops the reverse flow along the right side wall, directs the flow rearwards, and forms a recirculation bubble around the rear right corner of the hood. The air flow from the environment through the space between the right end of the up-blowing jet and the right side wall moves rearwards; it is deflected by the right deflection plate towards the central area, attracted by the entrainment effect of the up-blowing jet, and turns left and rearwards to form a large recirculation bubble (denoted by \(N_2\)) rotating counterclockwise. The video images recorded by the CCD camera showed clear rotation motion of the

![Figure 2](https://www.oup.com/academic/doi/10.1093/annweh/59.5.655/652196137)
vortices. The arrowheads shown in Fig. 3a indicate the visual rotation directions of the vortices. The same situation occurs in the area near the rear left corner of the hood and forms another pair of counterclockwise-rotating vortices in the left half of the hood. Therefore, as shown in Fig. 3b, four vortices (denoted by \( N_1, N_2, N_3, \) and \( N_4 \)) with neighbouring vortices rotating in opposite directions, appear in the horizontal plane \( z = 5 \text{ cm} \). Figure 3c shows the smoke flow images in the horizontal plane \( z = 45 \text{ cm} \). Four counterclockwise-rotating vortices appear. The vortices in the plane \( z = 45 \text{ cm} \) are closer to the rear wall and are smaller in size than those in the plane \( z = 5 \text{ cm} \).

Figure 4 shows the smoke flow images in the vertical plane \( x = 0 \). Below the sash bottom, at all face velocities (0.19, 0.26, and 0.32 m s\(^{-1}\)), regardless of whether the smoke was released in the hood from the work surface or with the up-blowing jet, the smoke was confined behind the up-blowing jet. Above the sash bottom, at a low face velocity of \( V_f = 0.19 \text{ m s}^{-1} \) (Fig. 4a,b), the smoke dispersed in the entire vertical plane. The images show that smoke in the space between the jet and the sash was thinner than that between the jet and the rear wall. However, in the region above the sash bottom, the smoke dispersed in the space between the jet and the sash at such a low face velocity that leakage of smoke was not observed near the sash bottom and sash opening. At \( V_f = 0.26 \text{ m s}^{-1} \) (Fig. 4c,d), the up-blowing jet was attracted by the rearward-offset suction slot and formed a rearward-inclined straight air curtain. Smoke was isolated in the IAC fume hood between the inclined air curtain and the rear wall. At \( V_f = 0.32 \text{ m s}^{-1} \) (Fig. 4e,f), a rearward-inclined concave air curtain was formed.

The smoke flow images in the horizontal planes of Fig. 3 show four vortices; neighboring vortices rotate in opposite directions. The smoke flow images in the vertical planes of Fig. 4 show that the vortical flows are rearward-inclined because they are isolated behind the rearward-inclined air curtain. In order to obtain threedimensional flow structures, STAR-CD, a computational fluid dynamics (CFD) commercial code, was used to calculate the flow field of the IAC hood. Figure 5 shows the streamline patterns of the calculation results. In the horizontal plane \( z = 60 \text{ cm} \), as shown in Fig. 5a, the streamline pattern clearly shows four vortices near the rear wall; each vortex rotates in a direction opposite to that of its neighbouring vortex—two behind the deflection plates and two in the central area. This scenario is quite similar to the flow visualization picture shown in Fig. 3. The front view shown in Fig. 5b indicates that these vortices are drawn by the suction force applied by the rearward-offset suction slot and form four ‘tornados.’ The streamlines present spiral motions from the work surface to the suction slot. Owing to the rotation motion of the flow, the static pressures within the ‘tornados’ are relatively lower than those in the environment surrounding the ‘tornados’ (Yuan, 1967). Therefore, the fumes are apt to be drawn into the four vortical flows (‘tornados’) and into the suction slot.
Figure 6 shows the smoke flow patterns around the sash bottom. When the smoke is released outside the hood and ejected towards the front surface of the sash, smoke streaks are observed, as shown in Fig. 6a. The smoke streaks move downwards along the front surface of the sash, separate from the sash at the junction of the sash and the boundary-layer separation controller (denoted by the 1st separation point), reattach to the boundary-layer separation controller at the location denoted by the reattachment point, and thus form a ‘slim’ recirculation bubble. Downstream of the reattachment point, the flow moves downstream along the boundary-layer separation controller and leaves the boundary-layer separation controller at the trailing edge (denoted by the 2nd separation point). After leaving the trailing edge of the boundary-layer separation controller, the flow curves up and forms a large recirculation vortex behind the sash, as shown in Fig. 6b. The photograph was taken by injecting the smoke towards the rear surface of the sash. Figure 6c shows a hand sketch of the flow topology. Owing to the arrangement of the boundary-layer separation controller, the separation point of the large vortex behind the sash induced by boundary-layer separation would not be close to the sash bottom (because the trailing edge of the boundary-layer separation controller is located in the hood at a distance from the sash bottom). Therefore, the risk of leakage induced by molecular diffusion, turbulence dispersion, and cross draft of the environment around the sash bottom may be decreased.

Figure 4  Smoke flow images in vertical plane \( x = 0 \) of IAC hood. (a–c) Smoke released from work surface, (d–f) smoke released with up-blowing jet. \( V_i = (a, d) \ 0.20 \mathrm{m/s}, (b, e) \ 0.26 \mathrm{m/s}, (c, f) \ 0.32 \mathrm{m/s}. \ V_b = 1.0 \mathrm{m/s}, H = 50 \mathrm{cm}. \)
Flow patterns of ineffective arrangements

Figure 7 shows the smoke flow images around the sash bottom when the boundary-layer separation controller was not installed. Both sash bottom configurations shown in Fig. 7 indicate that the boundary layer of the flow separates from the front edge of the sash bottom and forms a large vortex. It may be possible for the pollutants to be carried by the reverse flow towards the front edge of the sash bottom. Therefore, there may be a risk of leakage induced by molecular diffusion, turbulence dispersion, and cross draft of the environment around the sash bottom.

Figure 8 shows the situation in which the up-blowing planar jet of the IAC hood was removed—only the deflection plates and the narrow suction slot were functioning. Smoke was released from the work surface via two tubes. As shown in Fig. 8a, the smoke spreads over the entire horizontal plane. No apparent coherent flow structure is observed, such as those in Fig. 3. Near the two side walls, the smoke disperses outward, even though the deflection plates were installed. In the vertical plane at \( x = 0 \), as shown in Fig. 8b, the smoke disperses out of the hood face from the front edge of the work surface. Apparently, the flow field induced by this configuration

Figure 5  Streamlines obtained by CFD simulation. (a) horizontal plane \( z = 60 \) cm, (b) front view. \( V_f = 0.32 \) m s\(^{-1}\).

Figure 6  Smoke flow patterns around sash bottom of IAC hood. (a) smoke released from environment, (b) smoke inject behind sash and towards rear surface of sash. (c) hand-sketch showing flow topology. \( V_f = 0.32 \) m s\(^{-1}\), \( V_b = 1.0 \) m s\(^{-1}\), \( H = 50 \) cm.
without the up-blowing jet is not sufficiently robust to prevent leakage from the hood containment.

Figure 9 shows the situation in which the narrow suction slot of the IAC hood was replaced by a circular suction hole. The deflection plates were installed and the up-blowing jet was functioning. Smoke was released from the work surface via two tubes. The smoke spreads all over the horizontal plane behind the up-blowing jet. In reality, the smoke disperses and spreads all over the hood. Further, the smoke disperses towards the front edge of the hood occasionally through the spaces between the ends of the up-blowing jet and the side walls. As discussed by Huang et al. (2007b, 2010), by using a circular hole instead of a slot for suction, a “plane” push-pull air curtain would not be formed, even if a planar up-blowing jet was used. A three-dimensional flow field would be formed, and therefore, the smoke would spread all over the hood. This type of flow field is not sufficiently robust to prevent leakage from the containment because the contaminants present long residence time and wide dispersion characteristics in the hood. The presence of an operator and draft may adversely affect the containment performance owing to the accumulation of contaminants.

When the left and right deflection plates of the IAC hood were removed (i.e. only the narrow suction slot and the up-blowing jet were functioning) and the width of the up-blowing jet was extended to the side walls, it was observed that the smoke in the horizontal plane spreads over the entire plane above the work surface with random motion (similar to that observed in Fig. 9). The smoke released from the work surface is

Figure 7  Flow patterns around sash bottom of IAC hood without boundary-layer separation controller. (a, c) smoke flow patterns, (b, d) hand sketches showing flow topology. Smoke injected behind sash and towards rear surface of sash. (a, b) square sash bottom, (c, d) inner surface of sash attached with a half-circle rod. $V_f = 0.32 \text{ m s}^{-1}, V_b = 1.0 \text{ m s}^{-1}, H = 50 \text{ cm}$.
attracted by the entrainment effect of the planar jet and moves towards the front part of the hood. When the smoke reaches the up-blowing jet, it follows the path of the jet and moves up obliquely towards the suction slot. Thus, a large recirculation bubble is formed in the vertical plane. The recirculation bubble is isolated behind a rearward-inclined push-pull air curtain induced by the arrangement of the suction slot and the up-blowing planar jet (Huang et al., 2013). Although the smoke is stopped by the up-blowing jet, the large recirculation bubble induces long residence time of the smoke in the hood, and it is apt to the influence of drafts in the environment. Moreover, near the side walls, a risk of leakage may exist owing to the three-dimensional effect of flow.

From the previous discussion, it is clear that all four design elements (narrow suction slot, up-blowing planar jet, deflection plates, and boundary-layer separation controller) are critical to the effective performance of this fume cupboard design. The removal of even a single element would alter the flow structure and potentially result in leakage.

**Tracer-gas leakage concentrations**

The measured tracer-gas concentrations for the inner-plane test (static test) are listed in Table 1. At face velocities of $V_f \geq 0.26 \text{ m s}^{-1}$, the average leakage
Table 1. SF₆ leakage concentration of IAC hood detected by inner-plane test method (static test) based on EN-14175. ₇₅₅₆ cm, ₁₅₇ cm. Sampling grid locations refer to Fig. 2. All measured values of IAC fume hood can be denoted as <0.01 ppm.

<table>
<thead>
<tr>
<th>Hood type (width 150 cm)</th>
<th>( V_f ) (m s⁻¹)</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>Average</th>
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<tr>
<td>IAC hood</td>
<td>0.26</td>
<td>0.003 (0.007)</td>
<td>0.002 (0.006)</td>
<td>0.002 (0.007)</td>
<td>0.003 (0.006)</td>
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<td></td>
<td>0.32</td>
<td>0.002 (0.005)</td>
<td>0.002 (0.004)</td>
<td>0.001 (0.004)</td>
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<td>0.002 (0.003)</td>
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<tr>
<td></td>
<td>0.38</td>
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<td></td>
<td>0.45</td>
<td>0.003 (0.006)</td>
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Limit value set by France (AFNOR NF Standard X15-206, 2005)

0.10 ppm

Table 2. SF₆ leakage concentration of IAC hood detected by outer-plane test method (sash movement test) based on EN-14175. ₇₅₅₆ cm, ₁₅₇ cm. Sampling grid locations refer to Fig. 3. All measured values of IAC fume hood can be denoted as <0.01 ppm.

<table>
<thead>
<tr>
<th>Hood type (width 150 cm)</th>
<th>( V_f ) (m s⁻¹)</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>Average over II–V</th>
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<tbody>
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<td>IAC hood</td>
<td>0.26</td>
<td>—</td>
<td>0.002 (0.005)</td>
<td>0.003 (0.004)</td>
<td>0.003 (0.006)</td>
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<tr>
<td></td>
<td>0.32</td>
<td>—</td>
<td>0.002 (0.004)</td>
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<td>0.35</td>
<td>—</td>
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<td>0.38</td>
<td>—</td>
<td>0.002 (0.004)</td>
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<td></td>
<td>0.45</td>
<td>—</td>
<td>0.002 (0.004)</td>
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<td>0.003 (0.005)</td>
<td>0.003 (0.005)</td>
<td>0.003 (0.005)</td>
</tr>
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</table>

Limit value set by Germany (AFNOR NF Standard X15-206, 2005)

0.650
levels are $\leq 0.003$ ppm. These leakage levels, which are negligible, are significantly lower than the threshold value of 0.10 ppm set by France (AFNOR NF Standard X15-206, 2005) for the inner-plane test. The leakage levels for the static test of the IAC hood at a low face velocity of $V_f = 0.26$ m s$^{-1}$ are significantly lower than France’s threshold. The turbulence-induced fluctuations in the leakage levels of the IAC hood are apparently very small. We used higher sampling probe suction velocities of 30 and 60 cm s$^{-1}$ to measure the leakage values. The results showed similarly negligible leakage levels as those listed in Table 1.

The measured tracer-gas concentrations for the outer-plane test (sash movement test) are listed in Table 2. The average leakage values $C_{ave}$ over the time periods II–V at face velocities of $V_f \geq 0.26$ m s$^{-1}$ are lower than 0.004 ppm, and hence, they are significantly lower than Germany’s threshold 0.650 ppm. The maximum leakage values $C_{max}$ within all periods of measurement vary within a very small range and are lower than 0.008 ppm, which reflect the visualized stable flow field discussed in previous paragraphs.

The measured tracer-gas concentrations for the robustness test (simulated walk-by test) are listed in Table 3. The average leakage value of SF$_6$ at a face velocity of $V_f = 0.26$ m s$^{-1}$ is 0.328 ppm. The average and maximum leakage concentrations of SF$_6$ decrease rapidly with increasing suction velocity. At $V_f = 0.45$ m s$^{-1}$, $C_{ave}$ and $C_{max}$ decrease to negligible values—0.003 and 0.005 ppm, respectively. Compared with the thresholds (0.650 ppm) of Germany and the Netherlands (AFNOR NF Standard X15-206, 2005), the IAC hood exhibits very high robustness against the draft induced by walk-by motion.

**CONCLUSIONS**

An unconventional fume hood design, namely, the IAC hood, was developed and characterized using the laser-assisted smoke flow visualization technique and tracer-gas concentration detection method. The following conclusions were drawn from the issues discussed previously.

1. The IAC hood is characterized by four important elements: an elongated suction slot, an elongated up-blowing planar jet, two deflection plates, and a boundary-layer separation controller. The suction slot installed at an offset towards the rear wall and the up-blowing planar jet installed at the inlet region of the work surface formed a rearward-inclined push-pull air curtain to isolate the fumes generated in the hood. The deflection plates induced corner vortices when air was drawn from the environment into the hood, and subsequently, two large vortices were induced in the centre region of the hood owing to flow topology. Because of the combined effects of the rearward-offset suction slot, up-blowing planar jet, and deflection plates, four rearward-inclined vortical flows (‘tornados’) were formed. The fumes were entrained and confined within the low-pressure core of the vortical flows, inclined rearwards, moved up spirally, and exhausted through the suction slot.

2. The boundary-layer separation controller ‘forced’ the separation point of the boundary layer into the cabinet, thereby reducing the risk of containment leakage due to the large recirculation vortex usually found behind the sash of conventional hoods.

3. The IAC hood presented characteristics of low leakage and high resistance to dynamic disturbances at low face velocities. Tests conducted using the EN-14175 method showed that at a face velocity of 0.26 m s$^{-1}$,
the SF₆ leakage levels for the inner-plane test (static test) and outer-plane test (sash movement test) were lower than 0.003 ppm. The robustness test (simulated walk-by test) showed average leakages of 0.328 and 0.003 ppm at face velocities of 0.26 and 0.45 m s⁻¹, respectively.

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