Effects of Mannequin and Walk-by Motion on Flow and Spillage Characteristics of Wall-Mounted and Jet-Isolated Range Hoods

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Laser-assisted flow-visualization experiments and tracer gas concentration tests were conducted for the wall-mounted and jet-isolated range hoods to examine the physical mechanisms and relative magnitudes of hood spillages. The effects of a mannequin standing in front of the test rig and walk-by motions (which are situations always encountered in kitchens) were emphasized. The results showed that a mannequin (or a cook) standing in front of the counter would attract oil fumes toward the mannequin's body, induce large turbulent flows, and cause a significant dispersion of oil fumes into the environment through the front edge of the hood. Very high tracer gas concentrations were detected around the breathing zone of the mannequin. Increasing the suction flow rate did not reduce the spillage levels of the wall-mounted range hood but could moderately lower those of the jet-isolated hood. Serious spillages from both the wall-mounted and jet-isolated range hoods were detected as the simulated walk-by motion was performed. The jet-isolated range hood presented a much lower robustness in resisting the influence of people’s walk-bys than did the wall-mounted range hood. In summary, both the wall-mounted and jet-isolated range hoods were vulnerable to the influences of a cook’s presence and a cook’s walk-by motions. Increasing the suction flow rate might not obtain satisfactorily low spillages of pollutants but might increase noise level and energy consumption.

Keywords: flow visualization; hood spillage; range hood; tracer gas test; walk-by effect

INTRODUCTION

Cooking oil fumes are created and released into the environment when food is cooked at high temperatures. Stir frying and deep frying, for instance, are the cooking methods most likely to generate significant quantities of harmful cooking oil fumes (Tung et al., 2001). Exposure to cooking oil fumes has been recognized as a possible contributing factor to significant health problems. Some chemical substances (e.g. polycyclic aromatic hydrocarbons and carcinogen 2-amino-3,8-dimethylimidazo [4,5-f] quinoxaline) and particulates contained in the cooking oil fumes are the most notorious examples. The food flavoring diacetyl is also one of the contaminants of current interest. Degradation of sugar and fat, pyrolysis of proteins and amino acids, and other types of transformations that take place during high-temperature treatment of food can produce harmful degraded materials such as polycyclic aromatic hydrocarbons (Li et al., 1994). Particulates generated by cooking at high temperatures are another host of substances considered one of the main air pollutants in residential environments. See and Balasubramanian (2006) stated that the indoor air quality in and around food stalls may pose adverse health effects for people who experience long-term exposure to these cooking emissions. Siegmann and Sattler (1996) reported that the diameter and number concentration of the

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aerosols generated by heat-based cooking increased as the temperature increased. The mean diameter of aerosols generated by cooking usually ranged between 30 and 100 nm, and therefore, these aerosols could pass through the human nose and deposit themselves in the lower respiratory system.

The range hood is a fundamental and important appliance for the ventilation of kitchens and specifically for reducing the amount of cooking-induced harmful materials capable of accumulating in residential sites. Hoods are used to expel cooking oil fumes that, as just mentioned, have been linked to adverse health effects in kitchens. Previous studies on the performance of range hoods focused on the measurement and prediction of capture efficiency (Madsen et al., 1994; Li and Delsante, 1996; Li et al., 1997). Recently, the aerodynamics of range hoods has been the focus of studies regarding the indoor air quality in kitchens. Hunt and Ingham (1996) proposed a mathematical modeling technique to predict the airflow pattern around a state-of-the-art flanged exhaust hood reinforced by a turbulent radial jet. Abanto and Reggio (2006) predicted the airflow field in a kitchen by using a computational fluid dynamics method. Lai and Chen (2007) observed a strong kitchen-based thermal plume that caused ultrafine particles to present strong non-uniform concentration distributions in the kitchen. Lai and Ho (2008) reported spatially inhomogeneous distributions of particulate concentrations in a kitchen, and a significant concentration was detected near the stove. Chiang et al. (2000) and Lim and Lee (2008) presented numerical simulation results of the distributions of temperature and contaminant concentrations in a kitchen when cooking was taking place. Regarding these and other studies, most research results have implied that inappropriate flow patterns may be detrimental to the removal of the fume pollutants generated by cooking in the kitchen. However, the literature rarely presents detailed flow characteristics and their correlation with spillage relative to range hoods.

Previous research (Dai, 2009) has shown that considerable cooking oil fumes, when generated under the hood, tend to deflect toward the rear wall. If a cook stands in front of the counter, the body of the cook actually behaves like a ‘wall with a finite width’ or a ‘bluff body’. As the air is drawn by the fans of the range hood and passes over the cook, a complex airflow field inevitably emerges, induced by the interaction between the wall effect and the wake in front of the cook’s chest. The flow field would be complex with three-dimensional and turbulent characteristics. The combined effects induced by the suction flow, the wall effect, and the wake may be important to the spillage mechanisms affecting the efficiency of effluent pollutant evacuation. In addition to the effects attributable to the cook standing in front of the counter, the walk-by motion of the cook is important to the hood performance. Being used in kitchens, which are open spaces, range hoods can exhibit performances very sensitive to environmental drafts. The wake flow induced by the walk-by motion of kitchen occupants would create convective and turbulent currents and thereby could negatively affect a hood’s capture performance. However, very few studies address the influences of both a standing cook’s presence in front of a counter and the walk-by motions of kitchen occupants (especially kitchen personnel in a restaurant) on kitchen hood performance.

In this work, we studied the flow and leakage characteristics of wall-mounted and jet-isolated range hoods under the influences of both a mannequin standing in front of a counter and the walk-by motion simulated by a sweeping plate. More specifically, we examined the sectional flow patterns of the flow field under the hoods by using a laser light sheet-assisted flow-visualization technique. The tracer gas [sulfur hexafluoride (SF6)] concentration detection method served to evaluate the effectiveness of the hoods. Both the local leakages and the global capture efficiencies were measured. The correlation between the flow behaviors and the spillage mechanisms of the range hoods is presented and discussed.

EXPERIMENTAL METHODS

Apparatus

The test room’s dimensions were 18 × 18 × 5 m (length × width × height). With a special design, the draft level in the room was <0.03 m s⁻¹. Figure 1 shows the test rig, including the hood, counter, rear wall, heaters, and pans. A high-performance, up-suction, wall-mounted commercial range hood was mounted on the top of the test rig. The length, width, and height of the hood were, respectively, 90, 56, and 32 cm. The hood had partial side panels of curved bottom edges for mitigating the negative effect of cross-drafts. There were two suction fans installed in the wall-mounted range hood. An inverter could vary the flow rate of the suction fans. The experiments featured three total suction flow rates [suction flow rate in cubic meters per minute (CMM) (Qs) = 10.5, 12.0, and 15.0 m³ min⁻¹], which were measured by means of a calibrated venturi flow meter. The width, depth, and height of the countertop were 128, 62, and 84 cm, respectively. The distance
between the lower front edge of the hood and the countertop was $H = 60$ cm. Two electric heaters were installed on the countertop to simulate the stoves. The diameter of the hot plates of the electric heaters was 18.5 cm. When the flow-visualization experiments were conducted, two oil pans were put on the two electric heaters. The front and side views of Fig. 1 present the detailed dimensions and arrangements of the apparatus as well as the coordinate system $(x, y, z)$.

As the experiments for the jet-isolated hood were performed, three cross-flow fans were deployed on the countertop, forming a ‘U shape’ to enclose the hot plates, as shown in Fig. 1c. A long cross-flow
fan was parallel to the front edge and two short cross-flow fans were parallel to the lateral edges of the countertop. The cross-flow fans issued air jets upward from the slot exits. The width of the jet exit slots was 0.7 cm. The jet velocity was preset by the manufacturer and was adjustable at two values: $V_b$ (jet velocity in meter per second) = 3 and 4 m s$^{-1}$. The manufacturer of the jet-isolated range hood claimed that the U-shaped up-blowing slot jets, by isolating the cooking oil fumes in the domain enclosed by the three slot jets and the rear wall, therefore could improve the performance of the wall-mounted range hood.

For the experiments regarding the mannequin effect, a mannequin serving to simulate the effect of the cook was placed in front of the counter. The height and the shoulder width of the mannequin were 158 and 48 cm, respectively. The tip of the mannequin’s nose had a horizontal distance of $D$ (horizontal distance between tip of mannequin nose and front edge of counter) = 3 cm away from the front edge of the counter. The lower arms of the mannequin were posed at a height of 14 cm above the countertop.

For the experiments simulating the walk-by motion, a flat plate being 190 cm high and 40 cm wide was mounted upright with a distance $L$ (distance between plate and front edge of counter) away from the front plane of the counter, as shown in Fig. 2. The flat plate was driven by a motor sweeping across the front face of the hood from right to left to simulate the walk-by motion of a person at a speed $V_p$ (velocity of sweeping plate in meter per second). The traverse of the flat plate was extended for 60 cm on each side beyond the width of the hood.

**Flow visualization**

The flow-visualization method facilitated our observations of the flow patterns. A laser beam going out of a 100 mW Nd-YAG laser head (model: AMGC-100, Onset Electro-Optics Corp., Taipei, Taiwan) was directed to pass through a glass circular cylinder and expanded into a laser light sheet. The thickness of the laser light sheet was ~0.5 mm. The oil pans were filled with mineral oils having a boiling temperature of 280°C. During the flow-visualization experiments, the temperatures of the

![Fig. 2. Traversing mechanism and its deployment for walk-by experiments.](image-url)
hot plates and the oils contained in the pans were maintained at 360 and 230°C, respectively. The diameter of the oil fume particles was 1.7 ± 0.2 μm, as measured by a Malvern 2600C particle analyzer. The mineral oil fumes scattered the laser light and hence made the flow field above the countertop visible. A charge coupled device camera recorded the images of oil fumes in the plane of the laser light sheet. The framing rate and the exposure time were 30 fps and 1/60 s, respectively.

**Tracer gas test**

The current study employed the SF6 tracer gas concentration detection method to evaluate the performance of the wall-mounted and jet-isolated range hoods. The SF6 gas with a concentration of 99.99999% was released from small holes of homemade gas release rings, as shown in Fig. 3. The gas release rings were made of copper tubes with an inner diameter of 0.4 cm. In total, 20 small holes with diameters of 0.2 cm were drilled along each gas release ring to eject SF6 gas. A pressure gauge, a needle valve, and a calibrated rotameter were engaged to a piping system to control the flow rate of SF6. During the experiment, the gas release rings were attached to the hot plates of the electric heaters so that the SF6 gas would receive the heat and buoyancy from the hot plates, which were heated to a temperature of 360°C. The SF6 gas was released upward through the small holes. The flow rate of SF6 gas released from each gas release ring was 3 l min⁻¹ so that the exit velocity of SF6 from the ejecting holes was thus ~0.8 m s⁻¹.

For the local leakage tests regarding the mannequin effect, a stainless steel tube with an inner diameter of 13 mm was used as the sampling probe. The sampling probe penetrated through the head of the mannequin (which was placed in front of the counter and hood) so that the suction tip was positioned beneath the nose of the mannequin. The center of the sampling probe was 57 cm above the countertop. The distance D between the tip of the sampling probe and the counter front edge was 3 cm. The suction velocity of the sampling probe was 15 cm s⁻¹. As the capture efficiency was measured, the SF6 gas was first injected into the suction openings of the hood at a flow rate of 6 l min⁻¹. After traveling along an exhaust pipe (20 m long) for sufficient mixing, the concentration of the SF6 tracer gas was measured for 15 min in the exhaust at a location ~0.5 m upstream of the end opening of the exhaust pipe. The time-averaged value of the measured SF6 concentration was denoted as $C_0$ (time-averaged SF6 concentration, measured in exhaust pipe as a rated flow rate of SF6 gas, is injected into suction opening of hood during mannequin experiments). Subsequently, the SF6 gas of the same flow rate as used in the measurement of $C_0$ was ejected through the gas release rings, which had been placed on the hot plates of the electric heaters. Again, the SF6 tracer gas concentration was measured for 15 min at a point ~0.5 m upstream of the end opening of the exhaust pipe. The time-averaged value of the measured SF6 concentration was denoted as $C_1$ (time-averaged SF6 concentration, measured in exhaust pipe as an SF6 flow rate exactly as is the one used for measurement of $C_0$, is released from gas release rings during mannequin experiments). The capture efficiency $η$ [capture efficiency for static tests $(= C_1/C_0)$] was defined as the quotient of the $C_1$ divided by $C_0$, i.e. $η = C_1/C_0$.

For the local leakage tests concerning the walk-by effect, 8 and 12 sampling probes were, respectively, installed on the front ($y = 0$) and left lateral ($x = -66$ cm) planes, as shown in Fig. 4. The inner diameter of the sampling probes was 1 cm. The suction velocity of each sampling probe was 3 cm s⁻¹. For the global tests, a ‘spillage index’ $ζ$ [spillage index for plate-sweeping tests $(= C_3/C_2)$] is defined and discussed at the end of the Results and discussion.

Fig. 3. SF6 gas release ring for tracer gas concentration tests.
This index served to quantify the influence of plate sweeping on the performance of range hoods.

We used a Miran SapphIRe™ Infrared Analyzer to measure the concentration of SF$_6$ gas. The instrument is a single-beam infrared spectrometer that uses a pyroelectric lithium tantalite substrate as the detector. The lower and upper limits of SF$_6$ concentration that the instrument can detect are 0.001 and 100 ppm, respectively. The resolution is 0.001 ppm. The instrument was calibrated in house. The internal sampling rate of the detector is 20 readings per second. Averaged readings over 1 s were recorded as one data point so that each recorded datum represents an average of 20 readings sampled in 1 s. For each measurement of the mannequin test, the data of SF$_6$ concentration were continuously recorded for 12 min, that is 720 data points were obtained from 14 400 readings. Mean values of SF$_6$ concentration data were calculated by arithmetically averaging the recorded data over the end of the first minute to the end of the 12th minute.

The uncertainty estimates were based on the method of Abernethy et al. (1985). The total uncertainty $E$ of the variables could be found by combining systematic and random errors as $E = \sqrt{B^2 + (SD)^2}$, where $B$ was the systematic uncertainty, $SD$ was the standard deviation of the mean, and the degree of freedom $t$ was determined to ~2 for a 95% confidence level. The systematic uncertainty $B$ was estimated based on the calibration data and previous test experience, and the standard deviation of the mean $SD$ was computed from the raw measurement data. The accuracy of the suction flow rate measured by the venturi flow meter was within ±1.8%. The uncertainty of slot jet velocity measurements was estimated to be about ±0.4%. The tracer gas concentration measurements were conducted five times. For each run, the relative trends were similar. The data presented in this article were averages.
of five experimental results. The maximum difference of average values over 12 min from the five time-averaged values was less than \( \pm 0.002 \) ppm, which corresponds to a variation around \( \pm 0.004\% \) about the average value.

RESULTS AND DISCUSSION

Effect of mannequin on flow pattern

Figure 5 shows the typical flow patterns presented by the smoke traces in the symmetry plane \((x = 0)\) at \(Q_s = 10.5\) CMM. Figure 5b,c,d are for the cases without a mannequin standing in front of the counter. Figure 5a,d,e are the cases with a mannequin. The horizontal distance between the nose tip of the mannequin and the front edge of the counter is 3 cm.

For the wall-mounted range hood, as shown in Fig. 5a, the oil fumes rising from the top openings of the pans obviously deflect toward the rear wall. This phenomenon is induced by the Coanda effect (Newman, 1961), which is sometimes termed the ‘wall effect’ because the flow has a tendency to approach a wall that is located near the flow. As a flow or a jet goes along a wall with a narrow space between, low pressure may exist in the space between the flow and the wall due to the entrainment effect of the flow or jet and thus makes the flow or jet deflect toward the wall. In the present case, the rear wall does not allow the alimentation (i.e. entrainment) of the plume and therefore the plume is ‘pushed’ toward the wall. Since the oil fumes deflect toward the rear wall under the hood, an accumulation of condensed sticky oils on the rear wall under the range hood in the kitchen is commonly observed.

The flow patterns are highly turbulent as observed in the filmed recordings. Although not presented in Fig. 5a, obscure wafts of smoke near the front edge of the countertop are intermittently observable upon careful examination of these recordings. This smoke may be resulted from obstacle wakes, perturbations, flow separations, etc. Exchanges of mass and momentum through the turbulent diffusion mechanism will be natural, and therefore, dispersion of the oil

\[ V_b = 3 \text{ m/s} \quad \text{(wall-mounted)} \]
\[ V_b = 4 \text{ m/s} \quad \text{(jet-isolated)} \]

Fig. 5. Flow patterns depicted by oil fumes in symmetry planes under static condition. (a, c, e) unoccupied, (b, d, f) occupied, \( V_b = 3 \text{ m s}^{-1} \), \( H = 60 \text{ cm} \), \( Q_s = 10.5 \text{ CMM} \), \( D = 3 \text{ cm} \).
fumes into the atmosphere becomes inevitable. No dispersion of oil fumes was observed on the mid-
and upper portions of the plane from the front edge of the hood to the countertop. As a mannequin was
positioned in front of the counter, as shown in Fig. 5b, large amounts of oil fumes were attracted
from the region near the rear wall to the regions near the chest and nose of the mannequin. Inspection of
the films reveals that the flow took the form of violent tumbling and swirling motions and appeared to be
much more turbulent than its counterpart in Fig. 5a. An upward escape of oil fumes from near the hood
front’s edge into the atmosphere is apparent.

For the jet-isolated hood, as shown in Fig. 5c,e for
$V_b = 3$ and $4$ m s$^{-1}$, respectively, a wider spreading
of oil fumes toward the front face of the test rig was observable, particularly in comparison with the image shown in Fig. 5a. The flow fields under the hood, in reality, presented much stronger turbulence than their counterparts in the no-mannequin context. No boundary layer separation near the front edge of the countertop was observable in the films owing to the isolation effect of the up-blowing slot jet located parallel to the front edge of the countertop. When the mannequin was placed in front of the counter, oil fumes wafted toward the mannequin, traveled up along the chest and face, and ended with spillage from the area near the hood front edge owing to the combined effects of the wall and the wake. Leakages are obviously inevitable. Leakage of oil fumes at $V_b = 3$ m s$^{-1}$, shown in Fig. 5c, seems not as serious as the leakage taking place at $V_b = 4$ m s$^{-1}$, shown in Fig. 5f. A large jet velocity would induce higher degrees of entrainment and dispersion (Tennekes and Lumley, 1983) and, therefore, could exacerbate the leakage. Using the up-blowing jets on the countertop to enclose the oil fumes would not yield any significant positive effect regarding avoidance of the mannequin effect because the Coanda effect would deflect the jet itself toward a nearby solid wall.

According to Fig. 5b,d,f, large amounts of oil fumes were ‘attracted’ toward the front face of the hood as the mannequin stood in front of the counter. The ‘safety distance’, $D_s$ (i.e. the horizontal distance from the nose tip of the mannequin to the front edge of countertop, beyond which the wall effect would not be apparently observed), was measured by flow-visualization experiments and is noted here for readers’ reference. For the wall-mounted range hood, the safety distance was $\sim 11 \pm 2$ cm for all suction flow rates (10.5, 12.0, and 15.0 CMM) tested in this study. For the jet-isolated range hood with $Q_s = 10.5$ CMM and $V_b = 3$ m s$^{-1}$, a very long safety distance of $\sim 21 \pm 2$ cm is suggested. The safety distance becomes even longer ($D_s > 23$ cm) if the jet velocity $V_b$ is set at 4 m s$^{-1}$.

Flow patterns after plate sweeping

Figure 6 shows the flow patterns observed a few
seconds after the plate sweeping over the test rig, from right to left, at a velocity of $V_p = 1$ m s$^{-1}$. The distance between the plate and the front edge of the counter was $L = 0.5$ m. The suction flow rate was $Q_s = 10.5$ CMM.

The oblique top view of the horizontal plane located at 34 cm above the countertop of the wall-
mounted hood, shown in Fig. 6a, reveals that a large amount of oil fumes (i) rose from the pans being dragged to the left side of the test rig and (ii) propagated in an area far away from the hood’s capture zone. The oil fumes spread very widely, entering the atmosphere outside the view of the filmed scene. The films show that the dispersed oil fumes, being highly turbulent, therefore fluctuated and moved violently throughout the environment. A major portion of the spilled oil fumes eventually escaped capture by the hood and dispersed throughout the environment. Figure 6b shows the oblique left side view of the flow pattern in the plane at 10 cm away from the left side panel of the hood. A few seconds after the plate swept over the test rig from right to left, the oil fumes were dragged beyond the hood’s capture zone and appeared as a large clockwise-rotating vortex. Near the rear wall, a large amount of smoke accumulated. Apparently, the plate wake created a strong, turbulent vortical flow motion in the cooking area and forced the oil fumes under the hood out into the environment. The hood seemed to be very sensitive to the influence of walk-by motion.

Figure 6c,d, respectively, shows the flow patterns of the oblique top view of the horizontal plane at $z = 34$ cm and the oblique left side view of the plane at 10 cm away from the left side panel of the jet-
isolated hood at a few seconds after the plate’s sweep over the test rig. A considerable amount of the oil fumes spread out of the capture zone under the hood and dispersed into the atmosphere. The range and the intensity of this spread and this dispersal for the jet-isolated hood, as shown in Fig. 6c,d, appeared to be wider and stronger than the corresponding range and intensity for the wall-mounted range hood, as shown in Fig. 6a,b. An examination of the films reveals that the oil fumes (both those under the hood and those in the atmosphere) presented drastically stronger fluctuating and turbulent motions in the case of the jet-isolated hood than did the oil fumes in the case of the wall-mounted range hood. The side view films show strong upward currents agitated by the left slot jet.
By examining the films recorded during the flow-visualization experiments at various plate-sweeping velocities $V_p$ and distances between the plate and the counter’s front edge $L$, we observed and identified characteristic regimes for a ‘safe region’ (i.e. an area where no visible oil fumes spill out into the atmosphere) and those for an ‘affected region’ (i.e. an area where visible oil fumes spill out into the atmosphere), as shown in Fig. 7. The bands composed of short-slashed lines in Fig. 7 are the ranges where identification by visual inspection was difficult. These ranges comprised the border between the safe region and the affected region. The upper left hand part of the band belongs to the safe region, while the lower right hand part of the band is the affected region. As the suction flow rate $Q_s$ increased, the borders (i.e. the short-slashed bands) in-between these two characteristic regions moved toward the lower right hand corner. In other words, the affected region shrank as the suction flow rate increased. In this regard, the hood could remain safe for people walk-bys only if the distance $L$ between the plate and the counter’s front edge first increased as the plate-sweeping velocity $V_p$ increased. The dashed lines drawn in Fig. 7 show the upper thresholds of safe operation for walk-by velocities <$1\text{ m s}^{-1}$. For the wall-mounted hood, the upper threshold would decrease with an increase in the plate velocity. For instance, safe operations at $V_p = 1\text{ m s}^{-1}$ would require that the distance $L$ be longer than ~90 and 75 cm for $Q_s = 10.5\text{ CMM}$ and 15 CMM, respectively. Insofar as the walk-by velocity of kitchen occupants may vary from 0.4 to 1 m s$^{-1}$, imposing a safe distance longer than 75 cm for $Q_s = 15$ CMM would be an unrealistic way to satisfactorily address the real situations taking place in kitchens; furthermore, the real suction flow rate commonly used in residential kitchens is difficult to maintain and to use at the maximum rated value after installation because both piping can lead to drops in pressure and fan assemblies can deteriorate over time. Increasing the rated flow rates may increase the hood’s ‘robustness’ in resisting the influence of people walk-bys. This sequence of events, however, will result in greater noise and greater energy consumption. For the jet-isolated hood, the upper thresholds for the safe distance $L$ appear to be much longer than those of a wall-mounted hood operated under...
corresponding conditions. A safe distance $L > 95$ cm is a rule of thumb for large suctions, as shown in Fig. 7d–f,h,i. At the low suction rate of $Q_s = 10.5$ CMM with the high upward blowing jet velocity of $V_b = 4 \text{ m s}^{-1}$, the safe distance threshold is drastically $>95$ cm, as shown in Fig. 7g. The robustness (i.e., the capability of resisting the influence of walk-bys) of the jet-isolated hood obviously is lower than that of the conventionally used wall-mounted hood.

**Leakages subject to mannequin’s influence**

Figure 8 shows the typical time histories of SF$_6$ concentrations detected by the suction probe positioned under the mannequin’s nose at $D = 3$ cm and $Q_s = 10.5$ CMM. The detected SF$_6$ concentrations fluctuated drastically during the detection period and attained high values. These phenomena correspond to the flow-visualization results discussed in the above sections (see Fig. 5). Table 1 lists the time-averaged and maximum SF$_6$ concentrations that manifested themselves over a 12-min detection period for $D = 3$ cm. The average values of the wall-mounted range hood’s SF$_6$ concentrations attained the high level of $\approx 20$ ppm for all suction velocities: $\approx 17$ ppm at $Q_s = 10.5$ and 12.0 CMM and $21$ ppm at $Q_s = 15.0$ CMM. The maximum attained value was $\approx 50$ ppm, which implies that there were large ‘high-turbulence’-induced fluctuations occurring in front of the mannequin. The high values of the local SF$_6$ concentrations detected near the mannequin’s breathing zone suggest that a cook may risk high exposure to harmful elements contained in oil fumes when he or she works in front of the counter.

At $Q_s = 10.5$ CMM, the jet-isolated range hood at $V_b = 4 \text{ m s}^{-1}$ presented large average and fluctuating SF$_6$ concentrations [about $C_{\text{ave}}$ (time-averaged SF$_6$ concentration obtained by local measurements of plate-sweeping experiments) $\approx 18$ ppm; $C_{\text{max}} \approx 57$ ppm] near the breathing zone, levels that are the same as those associated with the wall-mounted hood. For the wall-mounted hood and the jet-isolated hood, the detected SF$_6$ concentrations at the jet velocity of $V_b = 3 \text{ m s}^{-1}$ were remarkably lower than those at $V_b = 4 \text{ m s}^{-1}$. A large jet velocity may induce large entrainment effect and turbulent dispersion and therefore leads to a larger spillage. This
phenomenon can be observed in the flow-visualization pictures of Fig. 5. The higher the suction flow rate the lower the detectable SF$_6$ concentration. However, even under the maximum suction flow rate of $Q_s = 15$ CMM, the detected SF$_6$ concentration level still attained $\sim 0.2$ ppm at $V_b = 3$ m/s$^{-1}$, which is not a negligible value. But it is apparent that the exposure risk run by a cook working in front of a jet-isolated hood operating at both a low jet velocity and a high suction flow rate can be lower than the corresponding exposure risk attributable to a wall-mounted hood.

Table 2 shows the results of a global test (i.e. the capture efficiency $\eta$) for the unoccupied (mannequin not installed) and the occupied (mannequin installed) cases under the static condition. The results of the capture efficiencies are listed in Table 2; although perhaps indicative of a hood’s overall performance, the variations of numerical values are not significant. The uncertainty of measurements, although is small, may still mislead the interpretations. Therefore, it is recommended that the interpretations for the capture efficiency data obtained in a well-controlled environment of low draft velocity for high-efficiency hoods should be very careful. To be conservative, only qualitative features of phenomena are described as follows. For the unoccupied condition, the capture efficiencies in all cases attain values >99% but <100%, an outcome indicating that leakages to the environment exist. For both the wall-mounted and jet-isolated hoods, increasing the suction flow rate would increase the capture efficiency. The capture efficiencies of the jet-isolated hood operated at mid- and high suction rates were a little higher than those of the wall-mounted hood for corresponding cases in the unoccupied condition. As the mannequin stood in front of the counter, the capture efficiencies decreased in all cases in contrast to the capture efficiencies where no mannequin had been installed. In contrast to the unoccupied condition, the capture efficiency of the wall-mounted hood decreased significantly while the suction flow rate increased (in the presence of a mannequin). Increasing the suction flow rate would induce a stronger wall effect and a stronger wake intensity in front of the mannequin’s chest and, therefore, would decrease the capture efficiency. The capture efficiencies of the jet-mounted hood operating at mid- and high suction rates under the occupied condition were higher than those of the wall-mounted hood for corresponding cases under the unoccupied condition, a phenomenon that is similar to the one characterizing the unoccupied condition.

According to the results presented in the above sections, the local flow visualizations and the local concentration measurements around the breathing zone of the mannequin seemed not to completely...
match the capture efficiencies obtained by means of the global measurement method. When referring to the capture efficiencies obtained by using the global test method, researchers will have difficulty in evaluating the exposure levels characterizing a cook who stands in front of a counter to prepare food. In contrast, the flow visualizations and the local spillage measurements around the mannequin’s breathing zone provide information of far greater detail for evaluating the cook’s exposure to harmful elements.

However, the results of local examination methods may not completely match the results of the global tests regarding a cook standing in front of a counter. This potential mismatch reflects the fact that kitchen hoods operate in an open space. The flow field is usually three dimensional, and thus, the pollutants may not spill from only one single direction, one single area, or a confined opening such as the chemical fume hood, which has five enclosure walls and one sash opening. Under this situation, the conventionally used ‘capture efficiency’ may not be the sole indicator for evaluating the functions of a range hood.

**Leakages subject to influence of plate sweeping**

Figure 9 shows the typical time histories of the SF₆ concentrations detected by the 20 suction probes (Fig. 4). For the wall-mounted hood, as shown in Fig. 9a, the time history of SF₆ concentration presents a hump that attains a peak value of ~18 ppm after a period during which the plate sweeps over the test rig. After the plate’s sweep over, the detected concentration did not fluctuate significantly.

For the jet-isolated hood, as shown in Fig. 9b,c, the spillages appeared much earlier than they did for the wall-mounted hood. At \( V_0 = 3 \text{ m s}^{-1} \), as shown in Fig. 9b, a peak attaining ~18 ppm appeared after the plate’s sweep over, followed by fluctuations smaller than the peak. At \( V_0 = 4 \text{ m s}^{-1} \), as shown in Fig. 9(c), the SF₆ concentrations fluctuated drastically, with the largest value ~24 ppm.

For various suction flow rates and plate-sweeping velocities, we calculated the time-averaged SF₆ concentrations (\( C_{\text{ave}} \)) of the time histories. The results are shown in Fig. 10, and the trends are similar to Fig. 9. For all suction flow rates where \( Q_s = 10.5, 12.0, \) and 15.0 CMM, the time-averaged SF₆ concentrations increased with the increase of the plate-sweeping velocity. The wall-mounted range hood presented much lower SF₆ leakages than the jet-isolated hood did. The spillages of the jet-isolated hood operated at a high jet velocity of \( V_b = 4 \text{ m s}^{-1} \) and at a low suction flow rate of \( Q_s = 10.5 \text{ CMM} \), as shown in Fig. 10a, are remarkably higher than in the other cases—it attained 7 ppm at \( V_p = 0.4 \text{ m s}^{-1} \) and 11 ppm at \( V_p = 1.0 \text{ m s}^{-1} \). Operating the jet-isolated

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### Table 2. Capture efficiency of unoccupied and occupied cases under static condition

<table>
<thead>
<tr>
<th>( Q_s ) (CMM)</th>
<th>Hood type</th>
<th>( \eta ) (%) Unoccupied</th>
<th>Occupied</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.5</td>
<td>Wall-mounted</td>
<td>99.38</td>
<td>99.21</td>
</tr>
<tr>
<td></td>
<td>Jet-isolated</td>
<td>99.39</td>
<td>99.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td>99.44</td>
<td>99.10</td>
</tr>
<tr>
<td>12.0</td>
<td>Wall-mounted</td>
<td>99.58</td>
<td>98.87</td>
</tr>
<tr>
<td></td>
<td>Jet-isolated</td>
<td>99.82</td>
<td>99.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>99.74</td>
<td>99.21</td>
</tr>
<tr>
<td>15.0</td>
<td>Wall-mounted</td>
<td>99.91</td>
<td>97.55</td>
</tr>
<tr>
<td></td>
<td>Jet-isolated</td>
<td>99.92</td>
<td>99.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>99.88</td>
<td>99.73</td>
</tr>
</tbody>
</table>

\( H = 60 \text{ cm}, D = 3 \text{ cm} \) for occupied case.
hood at low suction flow rate and high jet velocity would cause large turbulence dispersion due to mismatch of the ‘push jet’ and the ‘suction flow’ as discussed by Huang et al. (2005) and thus cause large spillage. The spillages at high suction flow rates were less serious than those at low suction flow rates. However, at the maximum rated suction flow rate of $Q_s = 15$ CMM, as shown in Fig. 10c, both the wall-mounted hood and the jet-isolated hood presented an unsatisfactory capability of resisting the influence of plate sweeping. For the wall-mounted range hood, the spillages were still not negligibly small because the plate-sweeping velocity $V_p$ was higher than $\sim 0.6 \text{ m s}^{-1}$. For the jet-isolated hood, the leakages presented high values even at the low plate-sweeping velocity of $V_p = 0.4 \text{ m s}^{-1}$.

Figure 11 shows a typical time history of the SF$_6$ concentration measurement for calculation of the spillage index $\xi$. The SF$_6$ gas was released with a flow rate of 11 min$^{-1}$ at time zero. Simultaneously, the concentration of SF$_6$ was measured for 12 min at a location $\sim 0.5$ m upstream from the exhaust pipe’s end opening, and the pipe had a length of 20 m. The recorded history of SF$_6$ concentrations went up from zero at time zero, attained an almost constant value before the plate swept over the test rig, formed a valley in response to the plate sweeping, and remained at an almost constant value subsequently. $C_2$ (time-averaged SF$_6$ concentration over a time history period of concentration measurements in exhaust pipe before plate sweeping during sweeping plate experiments) denotes the average value taken over the time period from the sixth minute to the ninth minute (when the recorded concentration attained a stabilized value before the plate swept over the test rig). $C_3$ (difference between $C_2$ and lowest SF$_6$ concentration induced by plate sweeping) denotes the difference between $C_2$ and the minimum SF$_6$ concentration at the valley. Using the integral average value over the period of the valley will be more suitable for considering the variations of curve aspect. We have tried this approach and found that the numerical values obtained by using the integral average value over the period of valley were lower than those by using the minimum SF$_6$ concentration at the valley as $C_3$, but the trends were similar. In order to prominently show the features, the minimum SF$_6$ concentration at the valley was adopted for $C_3$. We
defined the spillage index as $\xi \equiv C_3/C_2$ in order to quantify the extent of spillage when a hood is subject to plate sweeping. The larger the spillage index the more serious the spillage. Figure 12 shows the calculated spillage indices $\xi$ at the various suction flow rates of $Q_s$ and the various plate-sweeping velocities of $V_p$. The spillage indices shown in Fig. 12 match the phenomena presented by the local average measurements, shown in Fig. 10. All the hood spillage indices increased rapidly with increases in the plate-sweeping velocity. The spillage indices of the jet-isolated hood were apparently larger than those of the wall-mounted hood, particularly at the high plate-sweeping velocity. For the jet-isolated hood, the spillage indices for the cases operated at $V_b = 4 \text{ m s}^{-1}$ were apparently larger than those operated at $V_b = 3 \text{ m s}^{-1}$. A greater jet velocity did not mean greater resistance to walk-by motions. Increasing the suction flow rate could increase the robustness of the hood and make the spillage indices smaller. However, the improvements were limited because the values of spillage indices were not negligibly small even at the maximum rated suction flow rate of $Q_s = 15 \text{ CMM}$.

CONCLUSIONS

As a mannequin (or a cook) stands in front of a kitchen counter, oil fumes, which may contain substances harmful to human beings, waft toward the mannequin’s (or the cook’s) body owing to the complex interactions among the suction, wake, and wall effect. Three-dimensional, unsteady flow fields with very violent turbulent flow motions can form, thus causing large amounts of oil fumes to disperse into the environment through the front edge of the hood. In the current study, the tracer gas concentrations detected for the wall-mounted range hood around the breathing zone of the mannequin exhibited very high levels of spillages. Increasing the suction flow rate did not reduce the spillage levels. The jet-isolated range hood operated at a high suction flow rate, and a low jet velocity may reduce the tracer gas concentrations around the breathing zone of the mannequin when compared with the corresponding concentrations of the wall-mounted range hood, but the spillages detected there were not negligibly small. The results of the global tracer gas concentration detections under the static situation indicate that the capture efficiencies of the occupied condition were lower than those of the unoccupied condition for both the wall-mounted hood and the jet-isolated range hood. In contrast, the flow visualizations and the local spillage measurements around the mannequin’s breathing zone provide information of far greater detail for evaluating the cook’s exposure to harmful elements. However, the results of local examination methods may not completely match the results of the global tests regarding a cook standing in front of a counter due to the three-dimensional characteristics of flow. Under this situation, the conventionally used capture efficiency may not be the sole indicator for evaluating the functions of a range hood. Since the capture efficiencies detected in the environment with very low draft presented very high numerical values under all conditions and were not significantly distinguishable, it is suggested that
future research based on the experience from this study would be useful. As a plate swept over the hood and counter to simulate the situation of people’s walk-bys, the oil fumes easily spilled into the environment for both the wall-mounted hood and the jet-isolated range hood. The results of the tracer gas concentration tests, whether for the local spillage concentrations or the global spillage indices, reveal in general that the jet-isolated range hood had a much lower robustness than the wall-mounted range hood regarding the ability to resist the influence of people’s walk-bys. Overall, both the wall-mounted hood and the jet-isolated range hood are vulnerable to the influences of the presence of a cook in front of a counter and to the walk-by motions of kitchen occupants. Increasing the suction flow rate may not obtain satisfactorily low spillages of oil fumes. The authors therefore anticipate recommending new hood designs in order to overcome the existing aerodynamic deficiencies of the conventional hoods.

REFERENCES

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