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EVALUATION OF ENGINEERING CONTROLS FOR THE MIXING OF FLAVORINGS CONTAINING DIACETYL AND OTHER VOLATILE INGREDIENTS

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Abstract

Exposures to diacetyl, a primary ingredient of butter flavoring, have been shown to cause respiratory disease among workers who mix flavorings. This study focused on evaluating ventilation controls designed to reduce emissions from the flavor mixing tanks, the major source of diacetyl in the plants. Five exhaust hood configurations were evaluated in the laboratory: standard hinged lid-opened, standard hinged lid-closed, hinged lid-slotted, dome with 38-mm gap, and dome with 114-mm gap. Tracer gas tests were performed to evaluate quantitative capture efficiency for each hood. A perforated copper coil was used to simulate an area source within the 1.2-meter diameter mixing tank. Capture efficiencies were measured at four hood exhaust flow rates (2.83, 5.66, 11.3, and 17.0 cubic meters per minute) and three cross draft velocities (0, 30, and 60 meters per minute). All hoods evaluated performed well with capture efficiencies above 90% for most combinations of exhaust volume and cross drafts. The standard hinged lid was the least expensive to manufacture and had the best average capture efficiency (over 99%) in the closed configuration for all exhaust flow rates and cross drafts. The hinged lid-slotted hood had some of the lowest capture efficiencies at the low exhaust flow rates compared to the other hood designs. The standard hinged lid performed well, even in the open position, and it provided a flexible approach to controlling emissions from mixing tanks. The dome hood gave results comparable to the standard hinged lid but it is more expensive to manufacture. The results of the study indicate that emissions from mixing tanks used in the production of flavorings can be controlled using simple inexpensive exhaust hoods.

Keywords

mixing workers; exhaust hood; diacetyl; tracer gas testing; emission control; mixing tank

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INTRODUCTION

This paper describes a study designed to evaluate the effectiveness of engineering controls for mixing tanks used in the production of food flavorings containing diacetyl and other flavoring substances. Diacetyl has been used as one of the main components in butter flavoring that gives it a buttery taste. It has several synonyms including 2,3-butanedione; biacetyl; 2,3-butadione; 2,3-diketobutane; dimethyl glycol; dimethyl diketone; dimethylglyoxal; and dioxobutane (1). Diacetyl is used as a synthetic flavoring agent and aroma carrier in margarine, caramel, vinegar, and dairy products; it is also naturally found in some foods. It is commonly used in the flavor manufacturing industry throughout the production of flavor formulations.

Occupational exposures to diacetyl in the microwave popcorn and flavoring industries have been associated with respiratory disease, such as bronchiolitis obliterans. Bronchiolitis obliterans is a rare and life-threatening form of obstructive lung disease characterized by significant permanent decreases in pulmonary function. In May 2000, an occupational physician notified the Missouri Department of Health of a cluster of eight cases of this rare lung disease among individuals who had worked in the manufacture of microwave-buttered popcorn. Following the report of these cases, the Missouri Department of Health requested assistance from the National Institute for Occupational Safety and Health (NIOSH) in investigating the cause and extent of this disease. NIOSH conducted cross-sectional studies in six microwave popcorn plants. Five of the six plants had cases of airways obstruction among the workers (2). Respiratory symptoms and airways obstruction prevalence were higher in oil and flavorings mixers with longer work histories and in packaging-area workers near non-isolated tanks of oil and flavorings. Mean area diacetyl air concentrations were generally highest in the flavoring/oil mixing rooms and ranged from 2.88 to 57.2 ppm (3).

Similar respiratory disorders have been observed among workers who produce flavorings containing diacetyl (2, 4-6). In 1985, two workers with fixed obstructive lung disease suggestive of bronchiolitis obliterans were observed in a facility where flavorings with diacetyl were made for the baking industry (4, 5, 7). Since then, at least seven workers involved in the production of flavorings have been diagnosed with obstructive lung disease in California (8). Six of the seven workers job duties included compounding liquid and powder flavorings. One study evaluated diacetyl exposure in 16 flavor manufacturing companies (9). During liquid flavoring mixing, area diacetyl samples were below the limit of detection (LOD) for more than 50% of the samples with a mean of 0.80 ppm and a median of 0.05 ppm for 37 total samples.

Since mixing workers had the highest exposures and prevalence of airways obstruction, this engineering control study focused on controlling emissions from the mixing tanks, the major source of diacetyl in the workplace. The purpose of this study was to evaluate the efficacy of different hood designs for controlling vapors from flavor mixing tanks. Three exhaust hood designs (standard hinged lid, slotted, and dome) were evaluated along with two additional configurations for two of the hoods. Tracer gas tests were performed to evaluate quantitative capture efficiency for each hood. A perforated copper coil was used to simulate an area source within the 1.2-m diameter mixing tank. Capture efficiencies were measured at various hood exhaust flow rates and cross draft velocities. Target cross draft velocities were selected to cover the range of room air currents that might occur in flavorings plants.

METHODS

Liquid flavoring production process description

Flavor compounding and packaging are key steps in liquid and powder flavoring production (9). Compounding involves identifying the ingredients on recipes from batch tickets. These tickets identify the order and quantity of ingredients that need to be added to make a flavor formulation. Employees normally pour and mix small quantities of flavoring ingredients on a bench top. These precursor mixes often are combined with larger quantities of carrier liquids in large mixing tanks. Employees complete large pours, near open tanks often pouring directly into the tank. Following mixing, the finished product is packaged in containers and prepared for shipment.

Engineering control description

Three hood designs (standard hinged lid, slotted, and dome) were used throughout this study, with two designs each tested in two configurations. The designs and configurations were, as follows:

- hinged lid with open access port, hinged lid open (here after known as standard hinged lid, open);
- hinged lid with open access port, hinged lid closed (here after known as standard hinged lid, closed);
- hinged lid, slotted;
- dome, 38-mm gap; and
- dome, 114-mm gap.

Capture efficiencies were measured for each hood at various hood exhaust flow rates (2.83, 5.66, 11.3, and 17.0 m^3/min) and cross draft velocities (0, 30, and 60 m/min).

Each hood described below was designed to be mounted on a 1.2-m (4-ft) diameter mixing tank. This size tank was one of the larger tanks observed during surveys conducted in microwave popcorn and food flavorings plants. All hoods were fabricated by a sheet-metal contractor based on design sketches provided by NIOSH. Testing was conducted in a laboratory setting to allow for control of external variables. The room was enclosed and no external room supply air was utilized during testing.

Standard hinged lid-open and closed—A 1270-mm (50-in.) diameter lid was fabricated with a hinge at the centerline, which allowed it to be opened (Figure 2). A handle was mounted on the lid to facilitate opening and closing of the lid. The hood was equipped with a 203-mm (8-in.) diameter exhaust duct take-off. An access port [305 mm by 172 mm (12 in. by 6¾ in.)] was located on the lid to allow for pouring flavoring ingredients into the tank. This type of lid is frequently used in food flavoring mixing without the exhaust take-off.

Two configurations of the standard hinged lid hood were evaluated: open and closed. For the open test configuration, the lid was fully opened at the hinge. For the closed test configuration, only the small access port was open. The evaluation of these two configurations allowed for the assessment of two different modes of operation: one when a large opening was required (open configuration) and one when only a small opening (i.e., access port) was required to add small amounts of ingredients or pull quality assurance (QA) samples (closed configuration).

Hinged lid-slotted—This hood was similar to the standard hinged lid except for the addition of a 51-mm (2-in.) wide exhaust slot mounted under the lid (Figure 3). This slot was fabricated with a 25-mm (1-in.) flange and connected to the exhaust take-off through a plenum, which is mounted to the underside of the hood. The slot was braced by 25-mm wide stiffeners mounted 279-mm (11-in.) on center from the ends. The plenum was 1118-mm (44-in.) wide at the centerline hinge and tapers to the rear of the lid where the back of the plenum is 108-mm (4¼-in.) wide. The slot was included to provide more efficient collection of vapors across the tank open surface when the lid is open.

Dome hood—The dome hood configuration is shown in Figure 4. This hood allows for the efficient collection of vapors from the mixing tank while also permitting access to the tank through an integral door. A hinged access door was located three inches from the edge of the lid and was approximately 483-mm (19 in.) wide at the bottom and 279-mm (11 in.) wide at the top. The hood was equipped with a 152-mm (6-in.) diameter exhaust duct take-off. The dome hood was mounted on threaded rod allowing the hood height above the floor to be adjusted. It was envisioned that the dome hood would be permanently mounted to the exhaust system (i.e., fixed ventilation station) to allow the flavoring mixing tanks to be rolled under the hood to allow for ventilation, a common practice in industry. Since each tank used can be of a different size, there may be a gap between the top of the tank and the bottom of the hood. The dome hood was tested with two different gaps between the mixing tank and the bottom of the hood (see Figure 4): a 38-mm (1.5-in.) gap and a 114-mm (4.5-in.) gap.

Experimental ventilation control and measurement

Hood exhaust flow rate was monitored using an in-line averaging Pitot tube (delta tube model 306AZ-11-AO, Mid-West Instrument, Sterling Heights, MI) with an electronic manometer (VelociCalc Plus model 8386A meter, TSI Inc., St. Paul, MN). The averaging Pitot tube was mounted in accordance with the manufacturer's directions, and placed more than 17 diameters upstream and more than 12 duct diameters downstream of the nearest elbows. The duct pressure measurements were used to calculate airflow in the exhaust duct and recorded for every test condition. Hood exhaust flow rate was adjusted using a blast gate. Hood inlet air velocities were measured using the VelociCalc at several points across the hood face for each configuration and test condition.

Cross draft velocity was generated using a 762-mm (30-in.) industrial floor fan (Maxess Climate Control Technologies, Melville, NY) which was coupled to a variable autotransformer (Variac, Matheson Scientific). The fan was positioned to the side of the hood at approximately 1.83 m (6 feet) from the surface of the tank. The Variac was used to control the alternating current (AC) voltage delivered to the fan allowing control of fan speed and thus cross draft velocity. The cross draft velocity was measured at a distance of 152 mm (6-in.) from the edge of the hood orthogonal to the hood opening using a VelociCalc Plus model 8360 meter (TSI Inc., St. Paul, MN). The fan input voltage was set to provide target cross draft velocities of 0, 30, and 60 m/min to represent a wide range of potential room air disturbances.

Tracer gas evaluations

The primary method for evaluating the capture efficiency for the various fume hoods was through tracer gas testing. For this study, evaporation of chemicals was approximated using an area source consisting of a copper tubing coil. The tubing was perforated with uniformly spaced 1.5 mm (1/16 in.) diameter holes and was mounted inside a 1.2-m diameter mixing tank fixed 279 mm (11 in.) from the rim. Capture efficiency was measured quantitatively by releasing a tracer gas, sulfur hexafluoride (1% SF_6, balance N_2), at a constant rate inside the tank, then measuring the corresponding downstream SF_6 concentration inside the exhaust duct (see Figure 5). The SF_6 concentration was measured in the exhaust duct using a model 205B-XL MIRAN SapphIRe XL Infrared Analyzer (Thermo Environmental Instruments, Franklin, Mass.) and logged each second.

The hood capture test procedures were adapted from a European standard on the evaluation of capture efficiency using a tracer gas (10). The test procedure consisted of several steps, including measuring the:

1) pre-test background concentration ($C_{1(\text{pre-test})}$);

2) 100% capture concentration in the duct ($C_{2(100\%\ \text{capture})}$);

3) test phase concentration ($C_{3(\text{test phase})}$); and

4) post-test background concentration ($C_{4(\text{post-test})}$).

The initial background test was performed to evaluate and correct for the concentration of tracer gas in the ambient air within the room. Pre-test levels of tracer gas were recorded for at least a period of 3 minutes, which was denoted as $C_{1(\text{pre-test})}$. To minimize the potential impact of hood leakage on background tracer gas measurements, the room was ventilated between trials. The next step in the evaluation process was to release the tracer gas directly inside the exhaust duct to gauge 100% capture for a steady state period of at least 5 minutes, denoted as $C_{2(100\%\ \text{capture})}$. This SF_6 measurement in the duct represents the concentration if the contaminant were completely captured by the hood. Following the completion of the 100% capture measurement, the tracer gas was connected to the hood dispersal tube (simulating the emission of the actual contaminants) and exhaust duct concentration measurements were made for a period of at least 5 minutes to record the capture of the tracer gas during the test phase, denoted as $C_{3(\text{test phase})}$. This SF_6 measurement in the duct represents the concentration of the contaminant as captured by the hood. After the test phase was complete, the tracer gas flow was stopped, and post-test background levels were recorded for a period of at least 3 minutes, denoted as $C_{4(\text{post-test})}$. The $C_{4(\text{post-test})}$ was measured at least one minute after the tracer gas flow stopped.

The averages for the pre and post background measurements were subtracted from the means of $C_{2(100\%\ \mathrm{capture})}$ and $C_{3(\mathrm{test\ phase})}$, respectively and capture efficiency was calculated by equation (1) (10):

$$Capture \quad efficiency = \frac{C_{3(test \quad phase)} - C_{4(post-test)}}{C_{2(100\% \quad capture)} - C_{1(pre-test)}} \times 100\% \quad (1)$$

Figure 6 shows an example of the tracer gas test recording for a one trial of the hinged lid-open configuration under the low exhaust flowrate (2.83 m^3/min) and high cross draft condition (60 m/min). The capture efficiency for this trial was 78%.

For most trials, at least 50 seconds of data were averaged for the background calculations, and at least 100 seconds of data were used to calculate the test ($C_{3(\mathrm{test\ phase})}$) and 100% capture ($C_{2(100\%\ \mathrm{capture})}$) concentrations. The tracer gas used was released at a constant rate for the 100% capture and testing phase of each test to determine the capture efficiency during that test. However, the release rate was adjusted for each trial to provide a response within the range of the detector. The release rate varied from 0.35 to 2.12 liters per minute for these experiments, depending on the hood's exhaust volumetric flow rate—higher exhaust flow rates required higher tracer gas flows. Overall, there were nine unique test conditions for each hood configuration: three hood exhaust flow rates (2.83, 5.66, 11.3, and 17.0 m^3/min) by three cross drafts (0, 30, and 60 m/min). A minimum of three replicates of each test condition were conducted for hinged lid-slotted and hinged lid-open and closed hoods. A minimum of two replicates of each condition were conducted for the dome hood configurations. Trials were randomized for all exhaust flow rate and cross draft conditions by hood.

RESULTS

Figures 7 through 9 show the average capture efficiencies and standard errors for each hood across the nominal volumetric exhaust flow rates and cross draft velocities. The average relative standard deviation for each of the five designs was never greater than 2%. The average capture efficiencies ranged from 67% to 100% for all hoods analyzed under the various test conditions. The hinged lid-closed configuration had capture efficiencies above 95% for all conditions tested. Figures 10a and 10b show the airflow patterns created by the cross draft for the dome hood. As can be seen in these figures, the placement of the industrial floor fan on the left side of the hood causes smoke to escape from the mixing tank when the cross draft is applied.

Figure 7 shows the capture efficiencies when no cross draft was applied. Hood capture efficiencies ranged from 94% to 100%. The dome hood with a 114-mm gap had the lowest capture efficiency of 94% at the highest flow rate (17 m^3/min). This may have been due to the fact that higher exhaust velocities may have resulted in increased turbulence at the face of the hood causing leakage. The hinged lid-open configuration had average capture efficiencies of 100% for all the flow rates. At the lowest flow rate, the hinged lid-slotted hood had a capture efficiency of 97%.

Figure 8 shows hood capture efficiencies when a 30 m/min cross draft was applied. For all the hoods, capture efficiencies ranged from 73% to 100%. With the exception of the standard hinged lid-closed configuration and the dome hood with 38-mm gap, capture efficiencies dropped below 95% for all hoods at the lowest exhaust flow rate (2.83 m^3/min). The dome hood with 114-mm had the lowest capture efficiency of 73% at 2.83 m^3/min. The hinged lid-slotted hood had a capture efficiency of 85% at the lowest exhaust flow rate. At exhaust flow rates of 5.66 m^3/min or greater, all hoods achieved a capture efficiency of at least 90%.

Figure 9 shows the capture efficiencies when a 60 m/min cross draft was applied. Hood capture efficiencies ranged from 67% to 100%. The efficiency of all hoods dropped to below 90% at the lowest exhaust flow rate (2.83 m^3/min) with the exception of the hinged lid-closed configuration. The dome hood with 114-mm gap had the lowest capture efficiency of 67% at 2.83 m^3/min. At the lowest exhaust flow rate, the hinged lid-open configuration and hinged lid-slotted hoods had average capture efficiencies of 78% and 73%, respectively. At an exhaust flow rate of 5.66 m^3/min, the dome hood with 114-mm gap and hinged lid-slotted had the lowest capture efficiencies of 87% and 77%, respectively. With the exception of the dome hood (114-mm gap) and the hinged lid-slotted hood, all hoods captured at least 95% of the emissions at exhaust flow rates of 5.66 m^3/min or greater.

Average hood inlet air velocities for all hoods and test conditions are shown in Table I. The inlet air velocities ranged from approximately 4 to 280 m/min. The lowest inlet air velocities were measured on the hinged lid-open configuration. The highest velocity for this hood was 13 m/min at the maximum flow rate of 17 m^3/min while velocities, overall, were much higher for the closed configuration and ranged from 41 to 280 m/min. The hinged lid-slotted hood and dome hoods were similar in inlet velocities across the test conditions ranging from approximately 5 to 50 m/min from the lowest to highest exhaust flows.

DISCUSSION

All of the mixing hoods performed reasonably well with capture efficiencies above 90% for all hoods and configurations at an exhaust flow rate of 5.66 m^3/min and a cross draft of 30 m/min or less. The high capture efficiency of the standard hinged lid in the closed configuration was expected—the access port allows the addition of ingredients but maintains a high inward velocity at even low exhaust flow rates. The standard hinged lid in the open configuration provides a much larger opening for adding bulk constituents while the access port could be used for small volume additions and for the collection of QA samples. The dome hood with a 38-mm gap was also very effective but when the gap was increased to 114-mm, the performance suffered especially at lower exhaust flow rates (2.83 and 5.66 m^3/min). If this hood could be mounted directly on the tank (as a lid), performance would improve although usability would be impacted. The standard hinged lid in the open configuration had higher average capture efficiency than the hinged lid-slotted hood for almost all test conditions, and gave comparable results to the dome hood with the 38-mm gap except at the highest cross draft (60 m/min) and lowest exhaust flow rate (2.83 m^3/min).

The standard hinged lid with access port was the least expensive hood to fabricate at a cost of $1,502, whereas, the hinged lid-slotted hood cost $1,750. The dome hood was the most expensive at a cost of $2,267. With the standard hinged lid, the mixing tank lid could be closed when the tank was storing or actively stirring flavorings. The hood only needs to be opened when large quantities of chemicals are being added. The addition of the small access port allows the operator to check on the mix, add small amounts of chemicals, and pull samples for QA. Overall, the standard hinged lid gave the best mix of performance, flexibility, and cost among the hood designs evaluated. The dome hood gave comparable results, although, it is more expensive and performance is dependent on the size of the tank (i.e., the distance between the top of the tank and bottom of the hood—gap width).

The practical impact of these results can be evaluated based on measurements of area diacetyl concentrations in microwave popcorn mixing and flavoring compounding rooms. In environmental surveys conducted at six microwave popcorn plants, the area diacetyl concentrations measured in mixing rooms without local exhaust or general room ventilation ranged from 2.88 to 57.2 ppm (3). A study evaluating diacetyl exposures in 16 flavoring liquid plants, showed area diacetyl concentrations in the mixing rooms ranged below the limit of detection (LOD), 0.01 ppm, to 11 ppm with a mean of 0.8 ppm (9). Assuming that the sole source of diacetyl concentration in the mixing rooms came from the mixing tank, these area concentrations could be reduced to 0.005 to 2.86 ppm through the implementation of local exhaust ventilation such as those discussed here (based on a 95% reduction). Other potential sources of exposure include benchtop mixing and handling. Effective controls for these processes have been evaluated in flavoring manufacturing plants (11).

While this result indicates that mixing tank ventilation alone may not be sufficient to achieve airborne diacetyl concentrations below the NIOSH proposed recommended exposure limit (REL), 5.0 ppb, as a time-weighted average during a 40-hour work week, the use of these controls along with other exposure control measures could result in even greater reduction in mixing room concentrations and worker exposure (7). Additional measures could include process changes (e.g., reducing tank temperatures and incorporating closed transfer processes) or ventilation-based improvements (e.g., installing room exhaust ventilation). Although many job categories can be effectively controlled to levels below the draft REL, tasks associated with transfer of diacetyl may continue to pose risk to the workers even following the implementation of controls. However, these exposures can be reduced through the implementation of local exhaust ventilation approaches and closed transfer of flavoring substances.

A 3-year study of a microwave popcorn production facility showed that the use of exposure controls can dramatically reduce diacetyl concentrations in mixing rooms and exposures to all production workers (3). As a result of the implementation of exposure controls, average personal diacetyl air concentrations declined two orders of magnitude in the mixing room (from 57.2 ppm to 2.88 ppm) and the Quality Control laboratory (from 0.82 ppm to < LOD), and three orders of magnitude in the packaging area (from 2.76 ppm to < LOD for machine operators). These interventions included providing general room exhaust ventilation to the mixing room and local exhaust ventilation for the mixing tanks. Closed transfer processes were implemented through the installation of a pump to transfer heated butter flavorings from the holding tanks to oil/flavor mixing tanks. The building of an enclosure for all oil/flavor holding tanks and installing local exhaust ventilation on all tanks further reduced exposures to employees in the packaging area of this plant. In the final survey conducted following the implementation of all engineering and process controls, personal diacetyl exposures for all workers/job categories in the plant were below detectable limits with the exception of mixers, which ranged from below the LOD to 12.6 ppm.

It is important to note that although ventilated mixing hoods may reduce average worker exposure to diacetyl vapors, mixing workers may still be at risk from brief, peak exposures associated with open handling of flavorings or pouring of flavorings into heated tanks with oil (2). In the evaluations of microwave popcorn facilities, the plant with the lowest mean mixing room diacetyl concentration was the only one to have both local exhaust ventilation on the mixing tanks and general dilution ventilation with outside air. However, relatively high personal diacetyl air concentrations (>80 ppm) were measured over several minutes while the mixing worker poured liquid butter flavorings into the tanks with heated oil. The use of respirators for high exposure tasks, such as this, may be routinely required. However, the implementation of closed transfer systems is a preferred exposure mitigation approach.

The British Health and Safety Executive has developed an engineering control guidance sheet to contain emissions from mixing tanks outfitted with a ventilated hinged tank lid (12). This guidance sheet recommends an average inlet velocity of 30 m/min for flow into the hood. Average inlet velocities for the hinged lid-open configuration were lower than this recommendation and ranged from 4 to 13 m/min while the hinged lid-closed configuration was greater than 30 m/min for all exhaust flow rates. The hinged lid-slotted and dome hood were greater than 30 m/min at the highest flow rate (17 m^3/min). These results are not surprising as the hinged lid-open configuration has the largest amount of open tank area, while the closed configuration has the smallest. Although good capture was observed at exhaust flow rates greater than 11.3 m^3/min for all cross drafts velocities, higher exhaust flow rates may be required to account for tasks, such as, pouring liquids into the tank, which will displace vapor from the tank.

This study had a few limitations. Although the nominal cross draft velocities evaluated in the study were 0, 30, and 60 m/min, there was some variability associated with generating the actual cross draft. Specifically, at the lowest cross draft of 0 m/min, the actual measured cross draft ranged from 0.005 to 0.376 m/min with average velocities ranging from 0.117 to 0.234 m/min by hood type. The velocities at 0 m/min were much lower than typically encountered, but they were still not zero. Most indoor work environments (i.e., industrial and office settings) have been shown to average around 18 m/min (13). For this study, the cross drafts generated were higher than those typically seen in work environments but were used to evaluate worst-case conditions.

CONCLUSIONS

Based on past NIOSH studies, flavor mixing workers had the highest exposures and prevalence of airways obstruction among workers in microwave popcorn production plants (2). This engineering control study focused on the major source of diacetyl exposure in these plants: the mixing tank. This study shows that simple, relatively low cost hoods can easily be fabricated to address one of the primary sources of exposure to diacetyl in the production of microwave popcorn and food flavorings. The use of these hoods can dramatically reduce emissions of flavoring ingredients including diacetyl to the work environment. Because of the volatile nature of diacetyl and other flavoring chemicals, limiting the intensity and/or duration of worker exposure to vapors is essential. When working with flavoring ingredients, the use of closed transfer procedures is the preferred control technique. However, when closed transfer is not in place or feasible, these hoods can provide a reasonably effective approach to controlling evaporative emissions from mixing tanks during the production of flavorings and flavored foods.

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FIGURE 1.

Flavoring ingredients manually added to the mixing tank with a ventilated lid through an access port at a flavorings plant

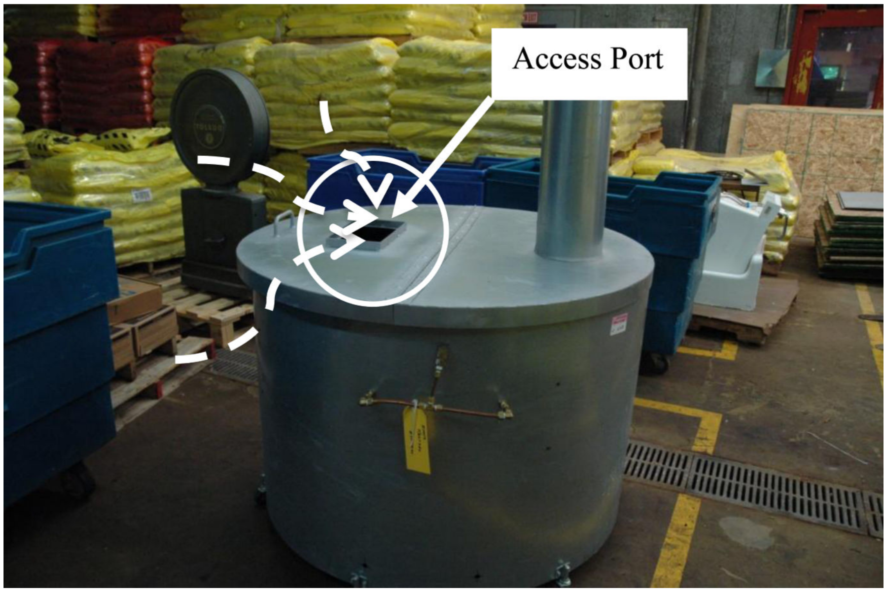

FIGURE 2.

Hinged lid-closed hood and exhaust configuration in test room (access port is shown) used in study. Note: Dashed arrows reflect airflow into the mixing tank.

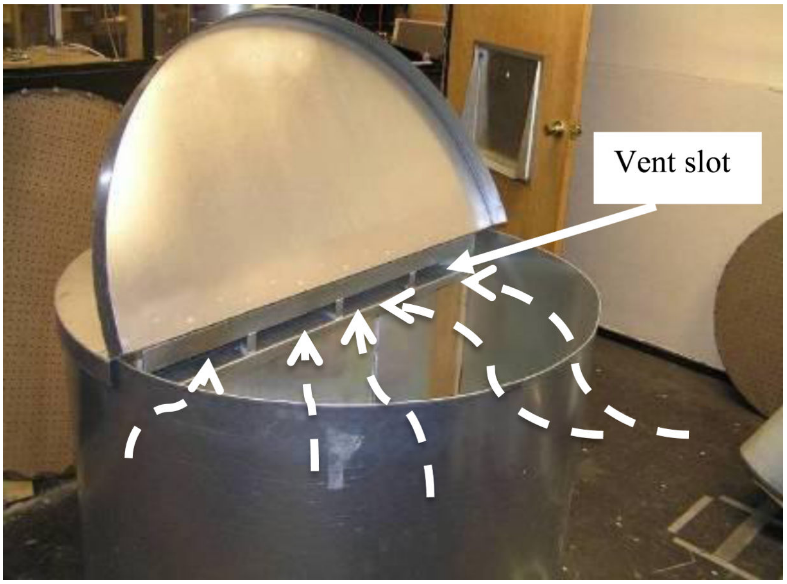

FIGURE 3.

Hinged lid-slotted hood and exhaust configuration in test room. Note: Dashed arrows reflect airflow into the mixing tank.

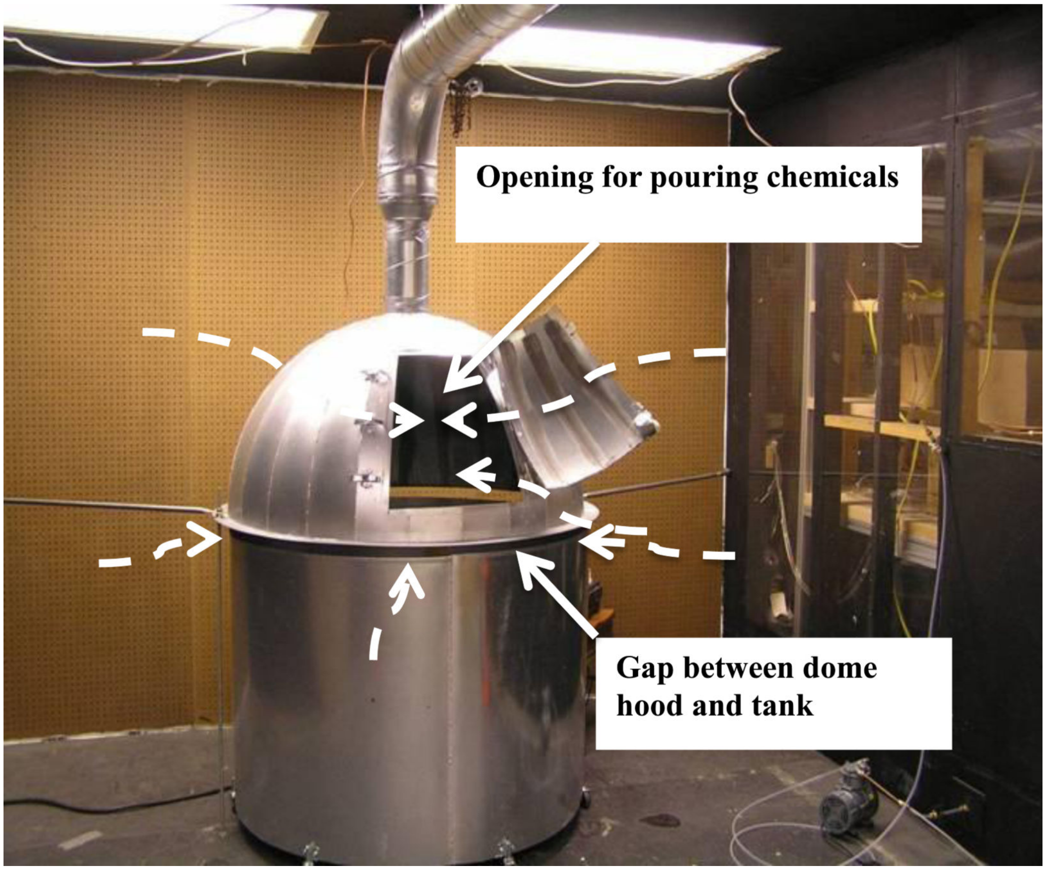

FIGURE 4.
Dome hood and exhaust configuration in test room. Note: Dashed arrows reflect airflow into the mixing tank.

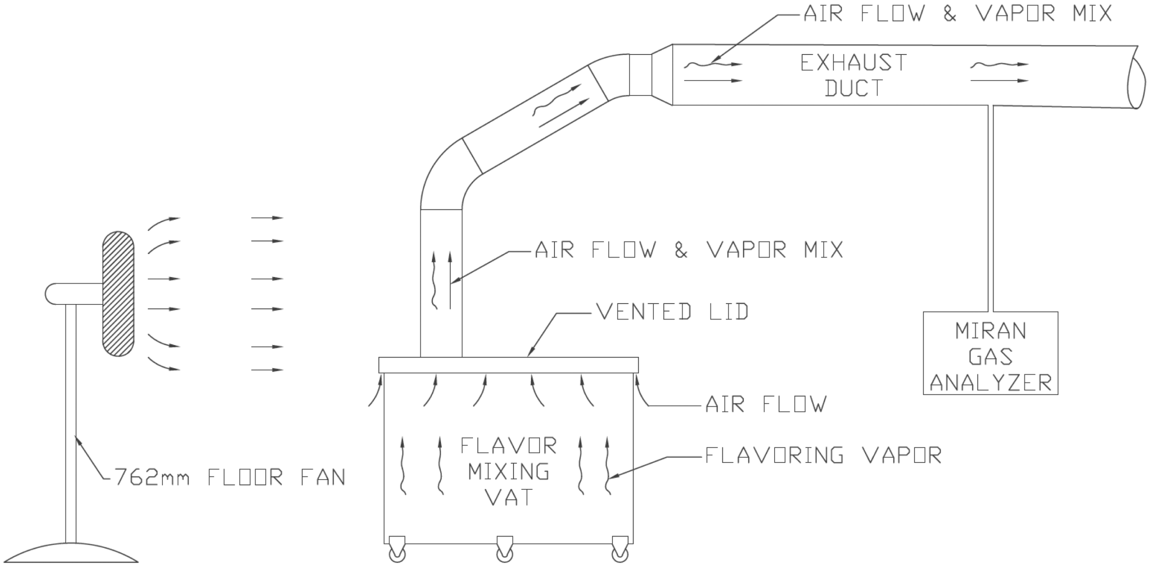

FIGURE 5.

Tracer gas sampling configuration with industrial floor fan 1.83 m from the surface of the tank

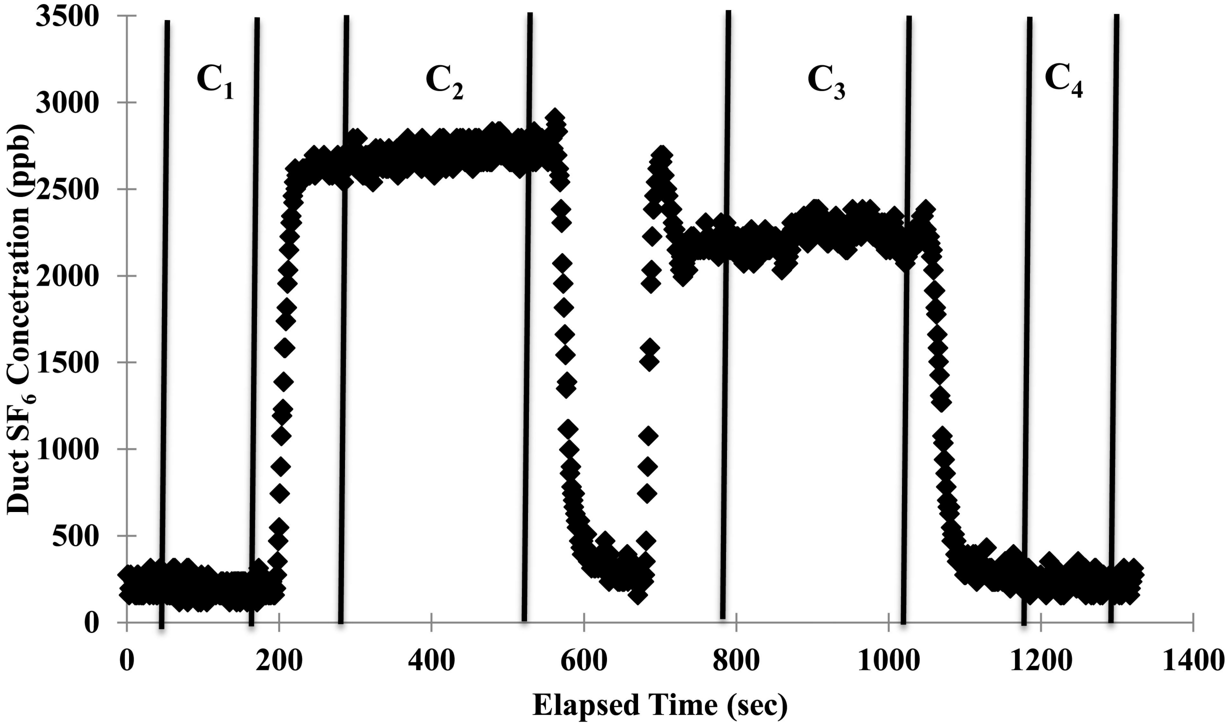

FIGURE 6.

Typical tracer gas testing of the hinged lid-open configuration (worst case scenario)

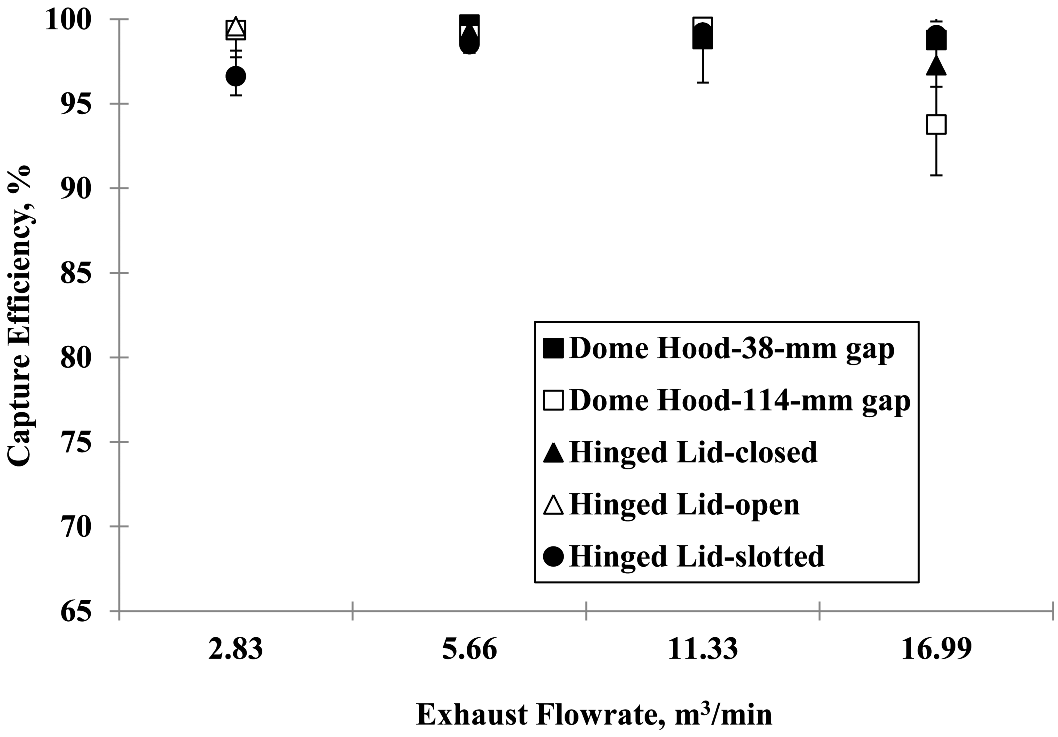

FIGURE 7.

Average capture efficiencies (with standard error) for each hood with no cross draft

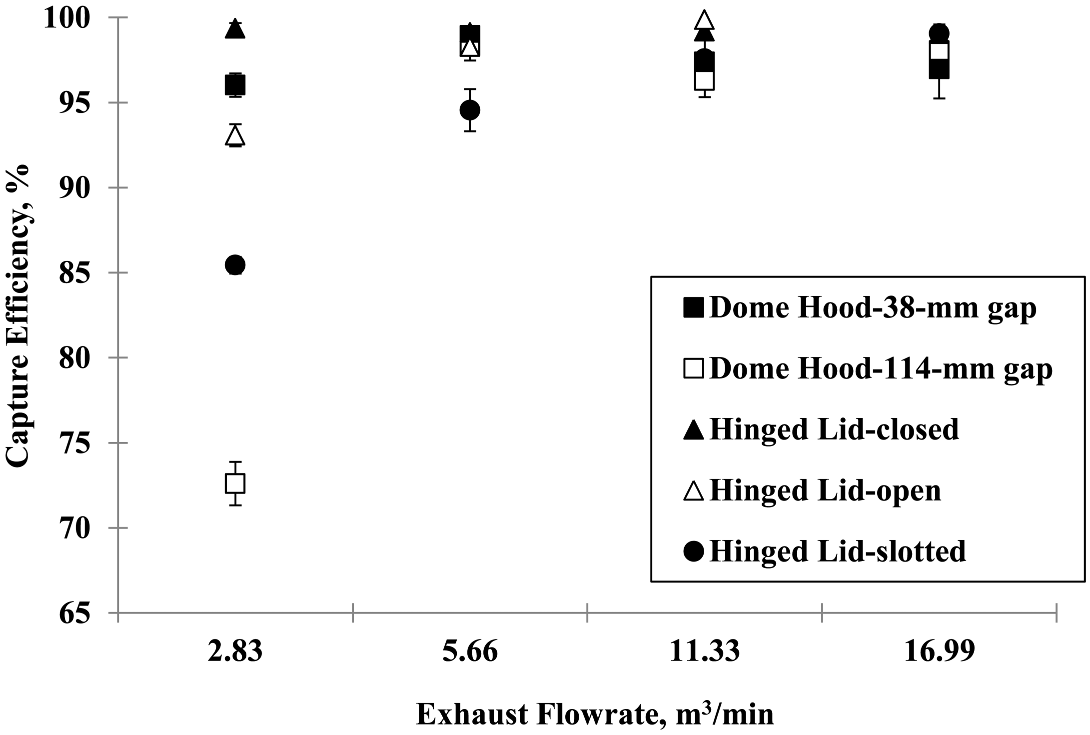

FIGURE 8.

Average capture efficiencies (with standard error) for each hood at 30 m/min cross draft

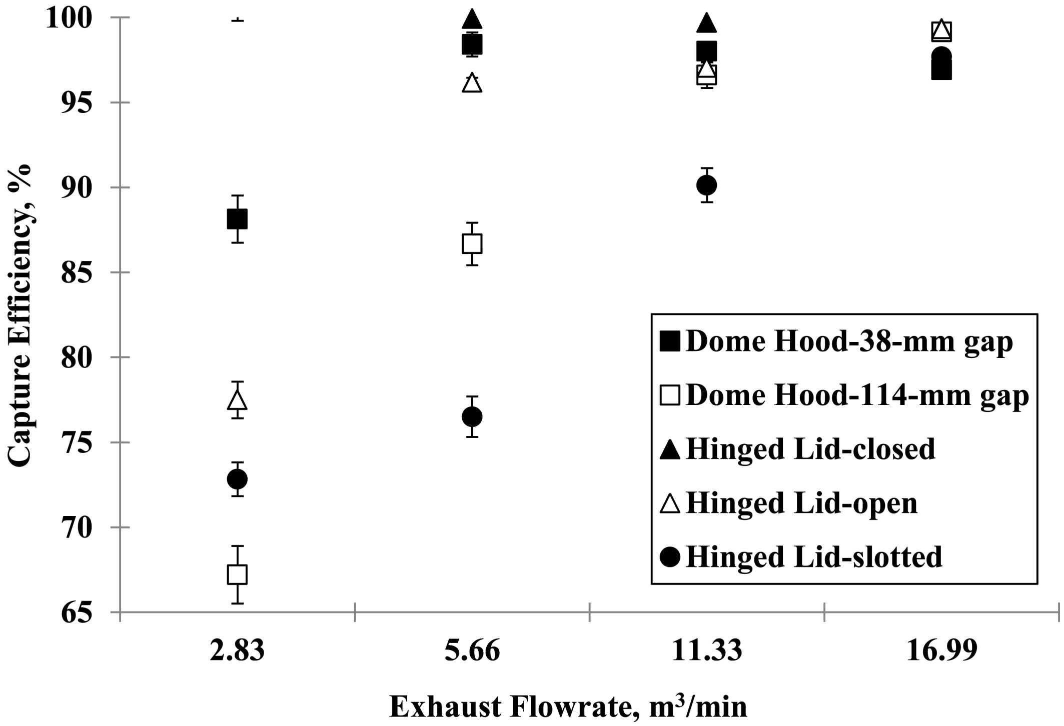

FIGURE 9.

Average capture efficiencies (with standard error) for each hood at 60 m/min cross draft

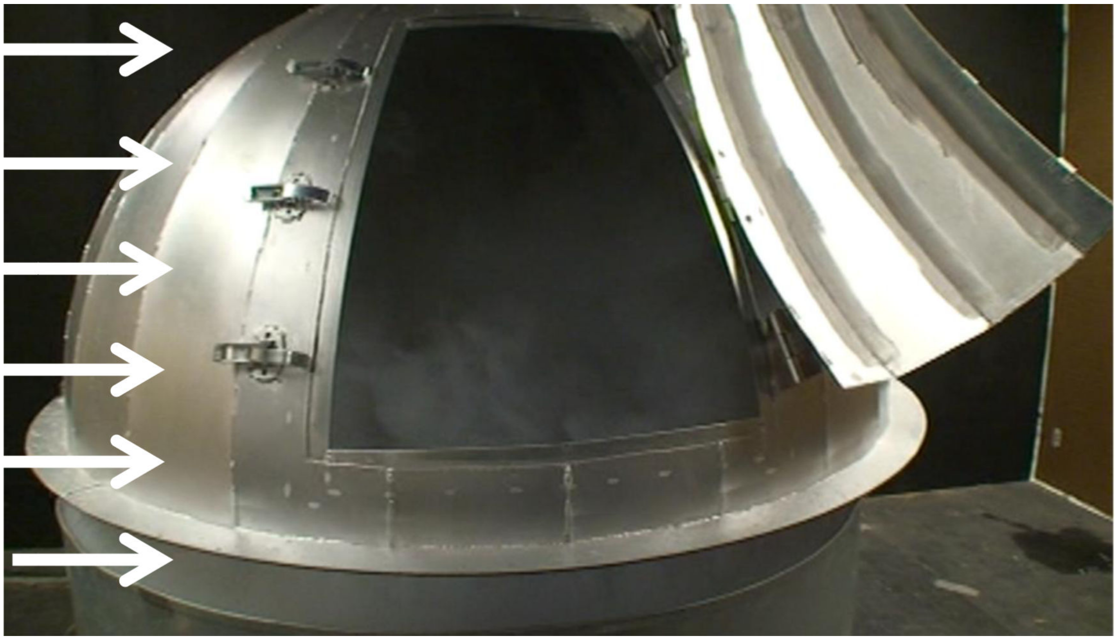

FIGURE 10a.

Dome hood with 114-mm gap (at 16.99 m^3/min and no cross draft). Note: White arrows reflect direction of airflow from industrial floor fan.

FIGURE 10b.

Dome hood with 114-mm gap (at 5.66 m^3/min and 30 m/min cross draft).

Note: White arrows reflect direction of airflow from industrial floor fan.

TABLE I

Average Hood Inlet Air Velocities (m/min)

Hood	2.83 m^3/min	5.66 m^3/min	11.3 m^3/min	17.0 m^3/min
Hinged lid-open	4.0	6.7	9.5	13.4
Hinged lid-closed	41.2	96.3	189.9	278.7
Hinged lid-slotted	5.2	13.7	27.1	33.2
Dome hood-38-mm	8.8	15.9	32.3	49.7
Dome hood-114-mm	4.0	6.7	9.5	13.4