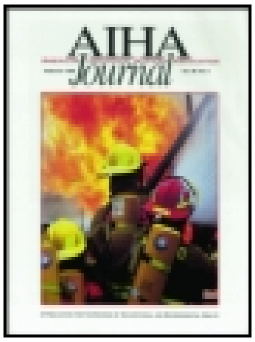

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Evaluation of Leakage from a Metal Machining Center Using Tracer Gas Methods: A Case Study

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Evaluation of Leakage from a Metal Machining Center Using Tracer Gas Methods: A Case Study

To evaluate the efficacy of engineering controls in reducing worker exposure to metalworking fluids, an evaluation of an enclosure for a machining center during face milling was performed. The enclosure was built around a vertical metal machining center with an attached ventilation system consisting of a 25-cm diameter duct, a fan, and an air-cleaning filter. The evaluation method included using sulfur hexafluoride (SF_6) tracer gas to determine the ventilation system's flow rate and capture efficiency, a respirable aerosol monitor (RAM) to identify aerosol leak locations around the enclosure, and smoke tubes and a velometer to evaluate air movement around the outside of the enclosure. Results of the tracer gas evaluation indicated that the control system was approximately 98% efficient at capturing tracer gas released near the spindle of the machining center. This result was not significantly different from 100% efficiency ($p=0.2$). The measured SF_6 concentration when released directly into the duct had a relative standard deviation of 2.2%; whereas, when releasing SF_6 at the spindle, the concentration had a significantly higher relative standard deviation of 7.8% ($p=0.016$). This increased variability could be due to a cyclic leakage at a small gap between the upper and lower portion of the enclosure or due to cyclic stagnation. Leakage also was observed with smoke tubes, a velometer, and an aerosol photometer. The tool and fluid motion combined to induce a periodic airflow in and out of the enclosure. These results suggest that tracer gas methods could be used to evaluate enclosure efficiency. However, smoke tubes and aerosol instrumentation such as optical particle counters or aerosol photometers also need to be used to locate leakage from enclosures.

Keywords: metalworking fluids, tracer gas

To reduce the risk of nonmalignant respiratory disease, the National Institute for Occuaptional Safety and Health has stated a recommended exposure limit of 0.4 mg/m³ as a time-weighted average for thoracic particulate mass or 0.5 mg/m³ for total particulate mass.[(1)] Because of adverse health affects associated with worker exposure to components of metalworking fluids including dermatitis,[(2)] respiratory disease,[(3)] and asthma,[(4)] worker exposure to airborne metalworking fluid mist needs to be controlled. Automated machining centers can be enclosed by the machine manufacturer and vented to an air cleaner to control the metalworking fluid mist emissions that are generated by the machining operations. The ability of these ventilated enclosures to prevent the emission of metalworking fluid mists into the workplace can be evaluated using tracer gas methods.

This article presents the findings of a tracer gas evaluation of an enclosure for a typical automated machining center during face milling operations. This evaluation was modeled after a successful tracer gas method used to evaluate asphalt paver engineering controls by the National Institute for Occupational Safety and Health.[(5)]A similar tracer gas method is an integral part of an American Society of Heating, Refrigerating and Air-Conditioning Engineers National Voluntary Consensus Standard for testing the performance of laboratory fume hoods (ANSI/ASHRAE 110–1985).[(6)]

Mention of any company or products does not constitute endorsement by the Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Presented at the Metal Working Fluids Symposium II, Detroit, Michigan, September 15–18, 1997.

METHODS

In an effort to evaluate the effects of engineering controls in reducing worker exposure to metalworking fluids, an evaluation of a metal machining center enclosure during face milling was performed at the General Motors Technical Center in Warren, Mich. The enclosure was built around a vertical metal machining center (LANCER®, Cincinnati Milicron, Cincinnati, Ohio) and an added ventilation system consisting of a 25-cm (10-inch) diameter duct, a direct drive, backward inclined centrifugal fan, and a three-stage filtration system that included a high efficiency particulate air filter. The ventilation system had two elbows between the machining enclosure and the air filter. In addition, there were two elbows downstream of the air cleaner. A diagram of the metal machining center and its major components is shown in Figure 1.

Tracer gas techniques were used to evaluate the enclosure's ability to control air contaminants and to measure the airflow into the hood. An aerosol photometer (RAM-1, MIE Inc., Bedford, Mass.), velometer, and smoke tubes were used to identify aerosol leakage and air movement near the enclosure. Pitot tube measurements were used as a backup method to evaluate airflow through the duct.

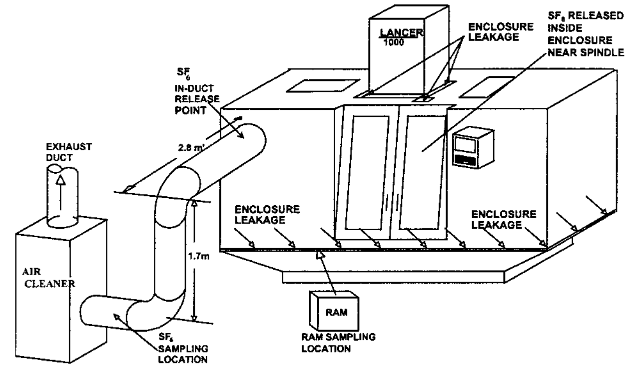

FIGURE 1. Illustration of machining center indicating leakage location, SF_6 release points, and RAM measurement location outside of the enclosure. There is a gap of about 0.6 cm between the upper and lower portions of the machining center.

Sulfur Hexafluoride (SF_6) Tracer Gas Test

A tracer gas, SF_6, was released at a known, controlled rate using a mass flow controller (FTS4, MKS Inc., Walpole, Mass.) to regulate the flow rate. To evaluate the enclosure and measure the airflow out of the enclosure, the SF_6 was released near the tool's spindle and in the duct. The concentration of SF_6 was measured with a photo-acoustic infrared detector (Multi Gas Monitor Type 1302, Bruel and Kjaer, Naerum, Denmark). The concentration was measured when the SF_6 was released into the duct and into the enclosure near the spindle. The SF_6 detector and the mass-flow controllers were calibrated prior to testing using standard concentrations of SF_6. The mass-flow controller was calibrated using a bubble meter and timer.

To measure the exhaust flow and the concentration at 100% capture efficiency, 1500 cm^3/min of pure SF_6 was released into the ventilation system. The SF_6 flowed through the flow controller and out of a 0.6-cm (¼-inch) diameter discharge tube. This discharge tube was placed into the duct near the connection to the enclosure. The SF_6 concentration was measured 14 duct diameters and 2 elbows downstream from where the duct connected to the machining center enclosure (Figure 1). The instrument's sampling probe was placed through a 0.6-cm (¼-inch) diameter hole in the exhaust duct and sampling was conducted perpendicular to the exhaust airflow. The 0.3-cm (⅛-inch) diameter tubing was connected to the open end of the sampling probe and to the detector. To obtain the enclosure's efficiency, the release point of the SF_6 was moved from the duct to a point in the enclosure near the spindle.

The 1500 cm^3/min of pure SF_6 was chosen to minimize the effects of SF_6 solubility in the metalworking fluid. SF_6 is slightly soluble in water (approximately 5.4 cm^3 SF_6/kg H_2O at 21°C).[7] During the testing a semisynthetic metalworking fluid was applied at a rate of 18 L/min), and this fluid could absorb as much as 0.097 L/min of SF_6. Thus, the SF_6 flow rate was high enough to keep the absorption rate below 6%.

The sampling location was chosen to ensure adequate mixing of the SF_6 tracer gas in the duct. Hampl et al. experimentally evaluated the effect of sampling location on SF_6 dispersion in ventilation systems.[8] In Hampl's work the SF_6 concentration was measured at different locations in the duct and the coefficient of variation (CV, the standard deviation divided by the mean expressed as a percentage) for these measurements was used as a measure of the dispersion of the SF_6 throughout the duct. When SF_6 was released from a single point or from four points in a straight run of duct, 25–50 duct diameters were needed to keep this CV below 5%. Apparently, the number of release points did not affect the dispersion throughout the duct. When the sampling and release locations were separated by 2 elbows and 10 duct diameters, the CV was under 5%.

The exhaust volume was computed as follows:

$$Q_{(exh)} = (Q_{(SF_6)}/C^*_{(SF_6)}) \times 10^6 \qquad (1)$$

where:

$Q_{(exh)}$ = flow rate of air exhausted through the ventilation system (m^3/min)

$Q_{(SF6)}$ = flow rate of SF_6 (m^3/min), and

$C^*_{(SF6)}$ = concentration of SF_6 (parts per million) detected in the exhaust duct when SF_6 is released in the exhaust duct.

Sufficient time was allowed between tests for the background readings near the SF_6 detector to drop below 0.1 ppm SF_6. Enclosure efficiency, η, was computed from $C^*_{(SF6)}$ and $C_{(SF6)}$, the concentration of SF_6 measured in the duct when SF_6 was released near the tool's spindle:

$$\eta = (C_{(SF_6)}/C^*_{(SF_6)}) \times 100. \qquad (2)$$

Background SF_6 concentration was monitored periodically to determine whether any SF_6 had accumulated in the test area.

Leakage Identification and Enclosure Flow Rates

The RAM continuously sampled the air near the gap between the upper and lower portions of the metal machining center enclosure. A straight piece of 0.6-cm (¼-inch) diameter Tygon® tubing was used to transport the aerosol from the gap to the inlet of the RAM. The RAM operated without its cyclone on the 0–2 mg/m^3 range and at a time constant of 2 sec. The RAM measures the quantity of light scattered by the entire aerosol cloud and provides a measure of relative concentration based on concentration and the aerosol's optical properties. The analog output of this instrument was recorded using a data logger (Ranger II, Rustrack, East Greenwich, R.I.).

TABLE I. Summary Statistics for SF_6 Concentration Measurements

	SF_6 Released in Duct	SF_6 Released in Enclosure
Mean (ppm)	98.1	96.3
Standard deviation (ppm)	2.3	7.5
Number of measurements	15	13

Smoke tubes were used to evaluate airflow qualitatively near suspected leaks from the metalworking machine enclosure and air movement within the enclosure. A velometer (Velocicalc, TSI Inc., St. Paul, Minn.) also was used to quantify the air movement near the identified leaks. Airflow within the duct was evaluated using the previously described SF_6 method and a pitot tube traverse. The 10-point, equal area pitot tube traverse was conducted in the duct upstream of the air cleaner to determine the average duct velocity and flow rate.[9]

RESULTS

The tracer gas concentration measured at the spindle and in the duct are reported in Table I. Based on the results of a pooled t-test for heterogenous variances, the concentration measured when the SF_6 was released at the spindle and in the duct did not differ significantly (p=0.2). However, the standard deviations did differ significantly (p=0.016). Within experimental error, the enclosure was capturing all of the tracer gas released at the spindle. Airflow through the duct based on SF_6 measurements was determined to be approximately 15.2 m^3/min (540 cfm).

The pitot tube traverse indicated that the average flow rate in the duct was approximately 14.7 m^3/min (521 cfm) based on an average velocity pressure of 14 pascals (0.057 inches water). This value was consistent with the tracer gas results. Smoke tubes were instrumental in identifying leakage near the base of the metal machining center. There was a 0.6-cm (¼-inch) gap between the top and bottom of the enclosure around the entire perimeter as shown in Figure 1. Leakage from the enclosure was visualized with smoke. The air motion induced by the metal removal spray generated by face milling appeared to cause the smoke to periodically flow out of the enclosure. Velometer measurements taken at the leak from the enclosure perimeter fluctuated between 1 and 3 m/sec (200 and 600 feet/min) out of the enclosure.

As depicted in Figure 2, aerosol photometer measurements showed that leakage occurred near a small gap between the upper and lower portions of the enclosure. The higher response depicted with a broken line was taken inside the duct, and the solid line depicts the readings taken near the base of the enclosure where aerosol leaked from the system. The solid line was cyclical and frequently moved between 0 and 1.5 volts, indicating peak concentrations of 1.5 mg/m^3 based on instrument calibration. These peak concentrations occurred when the spray from the face mill was directed toward the RAM's sampling location. Apparently, the airflow induced by the motion of the face mill and the fluid was blowing mist out of the enclosure. The three large pulses for the concentrations measured in the duct simply reflect the three separate 10-min test periods when the machining operation was being done.

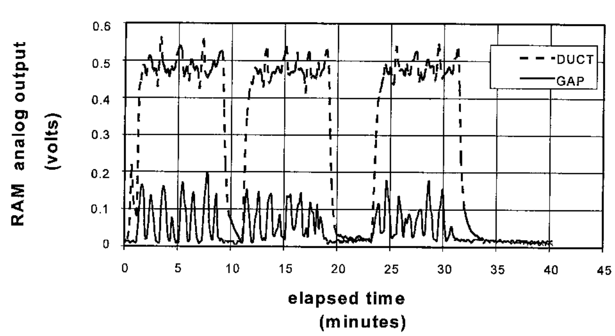

FIGURE 2. RAM analog output for mist concentration measured in duct and near gap between the bottom and top of enclosure. The RAM was set to the 0–2 mg/m^3 range and a 2-sec time constant. This plot shows three separate 10-min test runs.

DISCUSSION AND RECOMMENDATIONS

This study found that the enclosure was 98% efficient. When operated at a flow rate of about 15 m^3/min, this enclosure can help provide effective mist control. The increased standard deviation of the SF_6 concentration measured when the SF_6 was released near the spindle is informative and problematical. It could be indicative of either cyclic leakage or mixing problems. As a result of the increased standard deviation, the ability of the test to detect leakage was reduced. The confidence interval for the difference in the SF_6 concentrations was 1.8±5.4 ppm, based on a 95% confidence interval for heterogeneous variances. This indicates that the leakage out of the enclosure was less than 7%. The aerosol photometer, smoke tube, and velometer measurements indicate that leakage was actually occurring. However, such measurements do not reveal how much leakage was occurring.

The results presented here demonstrate that tracer gas methods augmented with velometer, smoke tube, and aerosol photometer measurements can be used to evaluate the ability of enclosures to control mist exposures. However, there are a number of practical issues that must be addressed.

The motion of objects such as the rotating tool and moving fluids will induce airflow.[10] This can force contaminated air out of the enclosure. Consequently, testing must be done with the metalworking fluid in the enclosure. The solubility of the SF_6 in the fluid is a concern. Based on a fluid flow rate of 18 L/min, the fluid could absorb a maximum of 6% of the SF_6. Based on the experimental variability, a 6% loss of SF_6 to the solution would not be noticeable in this work. In future work one must either account for the SF_6 loss to the fluid or set the flow rate high enough so that the loss is experimentally insignificant.

The velometer, smoke tube, and aerosol photometer measurements suggest that the leakage from the enclosure is a periodic function. The observed leakage occurred when the spray from the machine tool was directed at the left hand side of the enclosure in Figure 1. The air motion induced by the fluid motion apparently was blowing mist-laden air through the gap between the bottom and top of the enclosure. When the spray was directed at the right hand side of the enclosure, the leakage did not occur.

The cyclic nature of the mist emissions can cause increased variability in the measured tracer gas concentration and can cause biased measurements. By sampling a periodic phenomenon with instantaneous readings, the variability of the measured concentration can increase. In addition, the average of these instantaneous measurements may be biased. In this technique the SF_6 concentration was measured at a frequency of approximately 30- to 40-sec intervals (a frequency of 1.7/min). Examination of the aerosol photometer measurements in Figure 2 indicates that mist leakage

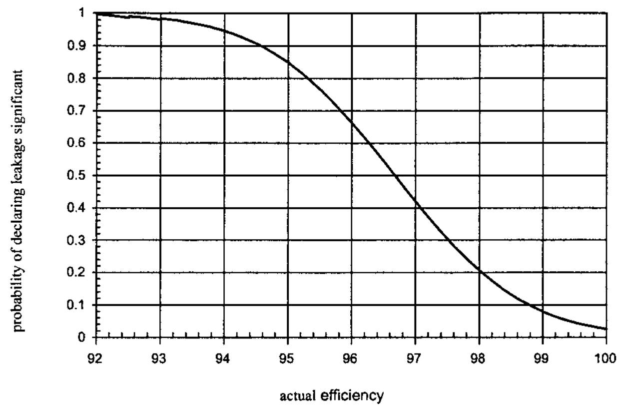

FIGURE 3. The probability of declaring that the measured tracer gas concentration differs significantly when the tracer gas is released in the duct as opposed to when the tracer gas is released in the enclosure. A pooled t-test conducted at the 95% confidence level is used to evaluate the significance of this concentration difference. This computation assumes that 10 concentration measurements were made at both release points and that the relative standard deviations were 2.5% for both release points.

has a frequency of about 1/min. Because the frequency of the SF_6 concentration measurement was less than twice the frequency of mist leakage, the average SF_6 measurements may be biased.[11,12] If the frequency of sampling and the frequency of the concentration fluctuations are nearly identical, concentration measurements will always be made at the same point in the concentration cycle and the measurements will be biased. The issues of bias and increased variability could be avoided by collecting an air sample in a gas bag over several complete production cycles. After allowing for adequate mixing in the gas bag, a sample from the gas bag is drawn into the instrument, which then measures the average concentration over the several production cycles.

The ability of tracer gas methods to identify leakage is limited by the precision of the tracer gas concentration measurement for the gas released in the duct and in the enclosure. A pooled t-test is used to evaluate whether these concentrations differ significantly. Figure 3 shows the probability that this test would declare that the concentrations are significantly different, indicating that significant leakage is occurring. The computation assumes 10 independent measurements for each location, a relative standard deviation of 2.5% for each location, and a normal distribution. In these conditions Figure 3 indicates that the tracer gas test can be used to ensure that collection efficiencies are better than approximately 93%. For these conditions there is a 95% probability of declaring that the measured collection efficiency is significantly less than 100%. This situation suggests a need either to improve the precision of the tracer gas concentration measurements or to quantify the percentage of escaping emissions (leakage) instead of the percentage of captured emissions. Unfortunately, the latter choice would require the placement of the enclosed machining center in a ventilated room and quantification of the amount of tracer gas in the air being exhausted from this room.

Enclosure control efficiency at a given airflow rate should probably be evaluated by the manufacturer before this equipment is sent to the user. The manufacturer could simulate machining operations with a metal removal fluid to generate realistic induced airflows. Aerosol photometers can be used to identify mist leakage, and tracer gas methods can be used to evaluate the overall efficiency of the enclosure. To maximize the reproducibility of data, the manufacturer would need to conduct this work at a test stand that has provisions for adequately mixing the tracer gas in the duct before the tracer gas concentration is measured. This may involve placing mixing baffles in the duct. A variable-speed fan would be needed to evaluate the effect of flow rate on mist leakage and overall enclosure leakage. The need to ensure adequate mixing of the tracer gas limits the utility of tracer gas methods in actual plants.

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