PS6-4 – 6155

Real-time monitoring of a flour mill fumigation with sulfuryl fluoride

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Abstract

Intensive data collection was conducted during a Sulfuryl Fluoride (ProFume®) fumigation in a 6-floor commercial flour mill to acquire data for the development and validation of Computational Fluid Dynamics (CFD) models of the fumigation process for methyl bromide alternatives. A weather station monitored barometric pressure, wind speed and direction, temperature, relative humidity (RH), and solar radiation. Inside the mill, a 3D anemometer monitored the mixture velocity, a pressure sensor measured the hydrostatic pressure, temperature/RH loggers obtained the temperature and RH profiles along the height of the mill, temperature cables attached to each wall of each mill floor (except the 4th) measured the wall surface temperature. Twenty concentration monitoring lines were placed throughout the mill. The concentration measurements were performed using two Fumiscope® Sulfuryl Fluoride sensors. The variation of the static pressure in the building followed that of the barometric pressure outside which indicates that the inside and outside pressures were coupled. The outside temperature varied between 19 and 30 °C. The inside temperature was higher than the outside temperature and increased linearly from 33 °C at the beginning of the fumigation to 35 °C toward the end. The anemometer measurements showed mostly low gas velocities (0.01 – 0.02 m/s). Although the concentrations at each location peaked at a different time, generally the locations on the same floors had maximum concentrations of similar magnitudes. The concentration maxima for the lower floors (the 1st – 3rd) were greater than for the top floors (the 4th – 6th). Most areas in the mill attained relatively the same concentration values within six hours of gas release. After peaking, the concentrations decayed at approximately the same rate yielding a half-loss time of approximately 17 hours.

Key words: Structural Fumigation, Methyl Bromide Alternative, Sulfuryl Fluoride.

Introduction

In the summer of 2005, a monitoring experiment was conducted as part of the annual fumigation

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of a commercial grain processing facility. The fumigant was ProFume®, a registered product name of sulfuryl fluoride (SF). The primary goal of this experiment was to acquire data for the development and validation of Computational Fluid Dynamics (CFD) models of the fumigation process for methyl bromide alternatives. These models are described in a second proceedings paper entitled Modeling the Structural Fumigation of Flour Mills and Food Processing Facilities by the same authors. The building was exposed to gas for approximately 24 hours, overlapping two days. The flour mill was sealed off from the other structures and thus only the environmental conditions and gas concentrations inside the mill were intensively monitored. Inside the mill, all elevator doors were closed, but the stairwell doors on the first, third, and fourth floors were left open. One shooting line and one corresponding circulation fan (2.71 m/s estimated) were assigned to each floor. At the beginning (1:45 pm of the first day), two cylinders of ProFume® were released to each floor of the mill building and after about two hours two additional cylinders were released to each floor. Each cylinder contained 56.7 kg of SF. The circulation fans on the first, fifth, and sixth floors were left running for the entire exposure period. The operation of the fans on the second, third, and fourth floors was controlled from outside of the building. These fans were turned off at 5:20 pm on the first day. They were turned on again at 11:00 pm of the first day and left running until 4:20 am of the second day. From that point on, they were off until the fumigation ended. The sealing material was removed beginning at 2:00 pm of the second day to start the aeration period. Around 3:00 pm, the building's ventilation system was turned on, removing the gas concentration by 6:15 pm after which the mill was entered to retrieve the data acquisition units and sensors as well as the bioassays. The bioassay experiment is presented in a third proceedings paper entitled A Preliminary Report of Sulfuryl Fluoride and Methyl Bromide Fumigation of Flour Mills.

Materials and methods

Facility

The commercial grain processing facility studied (Figure 1) is comprised of several connecting structures, i.e., a flour mill, truck and railcar loadout stations, a warehouse, a packaging area, and a maintenance building. The flour mill, which was the main focus of this study, has six floors with an approximate total volume of 28,317 cubic meters. The first five floors are constructed of precast concrete. Six-inch gaps between the edges of the floor plates and the wall panels allow air to circulate between floors. The five floors are interconnected by these gaps and several other openings for the manlift, piping and ducting. An elevator shaft and an adjacent stairwell are located relatively in the middle of the mill and can be accessed from all floors. An air supply system located on the sixth floor delivers fresh air into the mill through two cylindrical air supply ducts with perforated air outlets. The two ducts are located next to each other and run through the middle of the mill from the sixth to the first floor. The fifth and sixth floors are interconnected only through the elevator shaft, stairwell, manlift holes, and air supply ducts. The walls and roof of the sixth floor are constructed of insulated metal panels, which

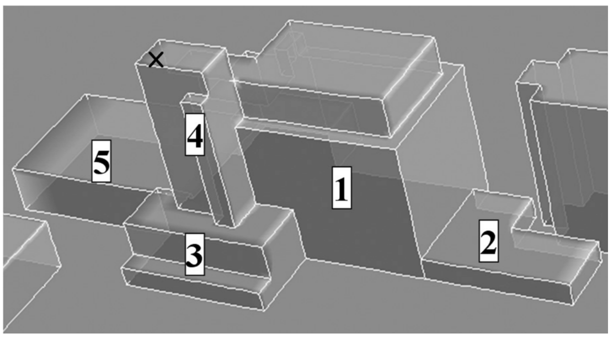


Figure 1. 3D drawing of the grain processing facility showing the flour mill (1), maintenance building (2), truck loadout station (3), packaging area (4), and warehouse (5). The weather station was located on the roof top of the grain processing facility at marked point ´.

are not as air-tight as the concrete walls of the other floors. Thus, when fumigated, any access from the fifth to the sixth floor is typically closed and sealed as much as possible. Also, the flour mill is usually sealed off from the connecting structures during a fumigation to minimize the loss of fumigant.

Data collection and equipment

As was observed in other studies (Chayaprasert et al., 2005; Cheong et al., 2003; Gilham et al., 2000), the dispersion pattern of gas is highly dependent on the fluid velocity field. Due to the size and complexity of the structure, it was not possible to obtain the actual fluid velocity field in the entire mill. However, measurements of gas velocity during fumigation would be beneficial for estimating fumigant distribution time. Hence, a data acquisition (DAQ) system, FieldPoint modular distributed I/O system (National Instruments Corporation, Austin, TX), with an ultrasonic anemometer (Model 81000, R. M. Young Company, Traverse City, MI) was located on the third floor of the mill in a relatively open area that was behind and at approximately a 7 m distance away from the circulation fan. Additionally, temperature and relative humidity (RH) were measured using a HMP2030 series sensor (Vaisala Inc., Woburn, MA) and hydrostatic pressure was measured using a Model 230-701 sensor (NovaLynx Corporation, Auburn, CA). The DAQ system collected the internal mill environmental data every one minute.

To obtain the temperature and RH profiles of the gas along the height of the mill, a temperature/RH logger (Hobo H8 family, Onset Computer Corporation, Bourne, MA) was placed near the center of each floor. In addition to the fluid temperature, a TMCx-HD temperature sensor (Onset Computer Corporation, Bourne, MA) was attached to each wall of the mill on every floor except the fourth floor to measure the wall's inner surface temperature. These temperature and RH data were collected every four minutes.

To monitor the outside weather conditions, a Hobo weather station (Onset Computer Corporation, Bourne, MA) was set up on the roof of the grain processing building at the highest location available (Figure 1). It monitored barometric pressure, wind speed and direction, temperature, RH, and solar radiation with a sampling interval of one minute. It was determined that at the highest location the measurement of wind velocity would not be affected by the recirculation zone that develops downwind above and behind the building (Chayaprasert et al., 2005). The anemometer was located at a height of three meters above the roof floor and measured wind speed and direction relative to the North.

A total of 20 concentration monitoring lines were laid out throughout the flour mill. The monitoring points were located at an approximate height of two meters above the floor. The number of monitoring points on the first, second, third, fourth, fifth, and sixth floors were two, four, six, two, four, and two, respectively. The labeling was done such that each label contained a floor index and a location index. For example, a label "M6_1" indicated a concentration monitoring point on the sixth floor at location number one.

Two Fumiscope® sensors were used to monitor gas concentrations at these locations synchronously. One was used for the odd numbered locations and the other one was used for the even numbered locations. The Fumiscope® sensor operates on the thermal conductivity principle, comparing the thermal conductivity of a fumigant/air mixture to that of ambient air (Key Chemical and Equipment, 2006). The difference is converted into an electric current proportional to the fumigant concentration. It has one sampling port into which the sampled gas is fed. The procedure for making one measurement with the Fumiscope® involves zeroing the reading, purging the monitoring tube corresponding to the desired location, connecting the monitoring tube to the Fumiscope®, adjusting the flow rate of the sampled gas to 7.87×10^{-6} m^3/s (1 standard cubic feet per hour), waiting for at least 30 seconds for the reading to be steady, and recording the reading, which needed to be executed manually. The time required for executing these steps was between three and five minutes. The gas sampling cycles started at the sixth floor and ended at the first floor and thus each cycle lasted 30 to 50 minutes. Gas samples were drawn through tubings, passed through the Fumiscopes, and routed back into the first floor of the flour mill. It is noted that due to an oversight the calibrations of the two Fumiscopes were not rechecked at the site before the fumigation started. However, they were re-calibrated before the last reading cycle ahead of unsealing. Although a difference of about 5 – 9 oz/Mcf between the two Fumiscopes was observed, the concentration data from both showed similar values and trends.

Results and discussions

Pressure

Figure 2 shows a plot of the pressures measured inside the structure and by the weather station (ambient). Between the time of the first gas release and the time of unsealing, the environmental barometric pressure continuously varied between 989 mb and 991 mb. The internal hydrostatic pressure varied in parallel to the external barometric pressure. It was consistently higher with an offset of approximately 5.5 mb. Given that the variation of the static pressure in the flour mill followed the variation of the barometric pressure outside indicates that the inside and outside pressures were coupled. Three factors influenced the difference in the pressure readings. One was the difference in the height locations of the sensors. The Hobo weather station was located at a much higher elevation (≈ 27 m higher) than the DAQ system. The higher the elevation, the lower the barometric pressure: The difference in elevation accounted for approximately 3 mb. The second factor was the inherent characteristics of the two sensors. When tested at the same condition, the NovaLynx internal sensor always showed higher pressures of 0.5 to 2.5 mb than the pressures of the Hobo weather station sensor. The reason for the differences in these test readings remain unknown. The last factor was the differences in the densities

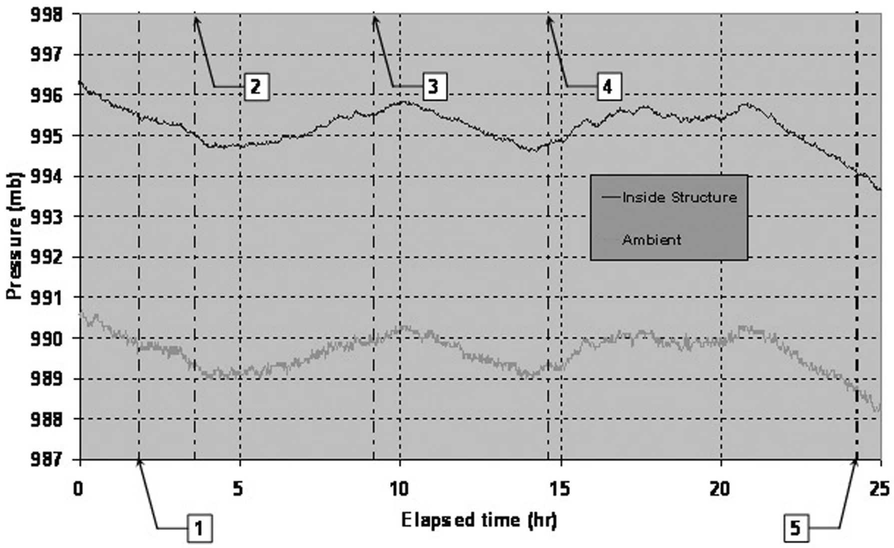


Figure 2. Pressure data from the DAQ system (inside the structure) and the Hobo weather station (ambient). The zero hour is the time when the first ProFume® introduction started. The first dash-dotted line (1.85 hr) is when the second ProFume® introduction started. The second and fourth dash-dotted lines (3.58 and 14.60 hr) are when the fans on the second, third and fourth floors were turned off. The third dash-dotted line (9.15 hr) indicates when these fans were turned on and the last line (24.23 hr) is when the structure was unsealed.

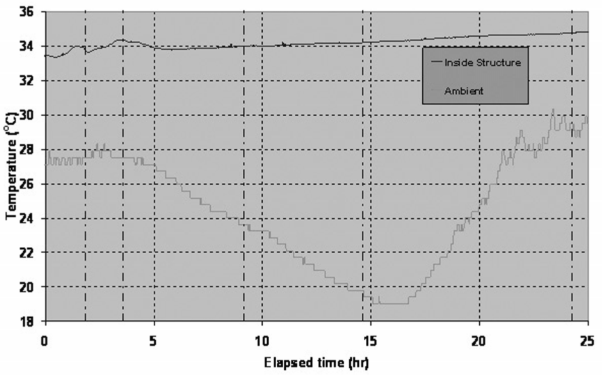
between the inside fumigant-air mixture and the outside air which created a difference in barometric pressure. This density difference effect is known as the stack effect. Assuming that the density difference was 0.1 kg/m^3, the pressure difference created by the stack effect in the mill could be at most 0.14 mb. Therefore, the offset pressure measurement is in the range of the summation of the pressure differences created by the three factors.

There was initial speculation as to whether an increase in the internal pressure due to the addition of the gas fumigant would be observed. Given the same amount of gas being released, if the mill was perfectly sealed, the hydrostatic pressure in the mill could potentially increase by 40 mb. However, looking closely at the internal pressure curve when the first (zero hour line) and second (first dash-dotted line) gas shots were released there was no noticeable increase in the pressure. The trend of the inside pressure was not affected and still followed that of the outside pressure. This implied that sealing did not create enough air-tightness to allow for an observable pressure build-up inside the mill. Another observation was related to the effect of the circulation fans on the static pressure inside the mill. At the times when the circulation fans on the second, third and fourth floors were either turned off (second and fourth dash-dotted lines) or on (third dash-dotted line), the pattern of the inside pressure still followed that of the outside pressure. This implied that the operation of the circulation fans did not have any influence on the static pressure in the mill. Considering that this flour mill is relatively new and was built to be more air-tight than older structures, the same observations are expected in any other grain processing structure.

Temperature and RH

Figure 3a is a plot of the temperature measured by the DAQ system and the weather station. The outside temperature varied between 19 and 30 °C. The temperature inside the mill was higher than the outside temperature and increased relatively linearly from 33 °C at the beginning of the fumigation to 35 °C toward the end. It was somewhat unexpected that the inside temperature continuously increased (except on the sixth floor), especially during the night time when the outside temperature was relatively much lower. Considering that concrete is a good insulator, the explanation for this observation could be the fact that the flour mill was a sealed concrete structure containing various types of heat sources. The primary heat source was the lighting system which has a total power of 52,423 Watts. The data from the Hobo temp/RH loggers (not shown) indicated temperature stratification within the mill. The higher

(a)



(b)

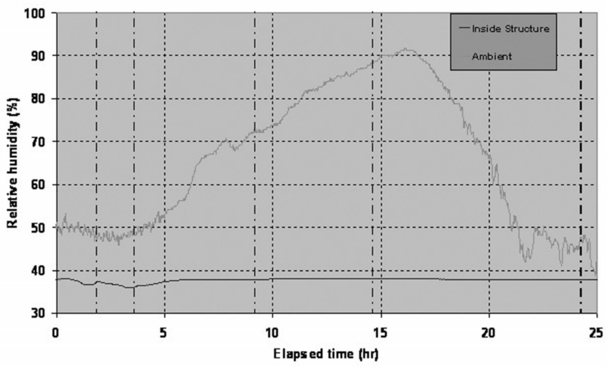


Figure 3. (a) Temperature and (b) relative humidity data from the DAQ system (inside the structure) and the Hobo weather station (ambient). Refer to Figure 2 caption for explanation of the dash-dotted lines.

floors tended to have higher temperature resulting in a difference of approximately 3 °C between the first and the fifth floors. There was no substantial difference between the third floor air temperature measured by the Vaisala VS. Hobo sensors. A plot of the RH data is shown in Figure 3b. The correlation between temperature and RH is inverse proportional. As temperature increases, RH decreases and vice versa. The outside RH was lower during the day time and increased in the night time. Based on the psychrometric properties of air, the outside temperature and RH variations indicated only slight changes in the absolute humidity which implies that the weather was stable. Due to the relatively constant temperature in the mill, the inside relative humidity stayed relatively constant for the entire exposure period. Stratification of the RH among the flour mill floors was observed (data not shown) and was consistent with the observed temperatures.

Wind velocity and direction

The wind speed and direction during the fumigation are shown in Figures 4a and 4b, respectively. The wind speed varied between 0 and 6 m/s (13.42 mph). The wind direction changed little during the night time and was primarily from the North-East. However, during the day time the wind direction drastically fluctuated from all angles. In general, the effect of wind directions on the fumigant leakage rate depended on the layout of the structures surrounding the fumigated structure because the surrounding structures in the upwind region would reduce wind speed and thus the stagnation pressure acting on the downwind fumigated structure's wall.

Velocity of the gas in the structure

Figure 5 displays the velocity magnitude of the fumigant-air mixture measured by the DAQ system. During the first and second gas releasing periods, gas movement was above 0.12 m/s and thus observable. Forced movement (>0.2 m/s) of the gas also occurred when the ventilation system was turned on. During the exposure period, gas movement due to natural convection was minimal and resulted in velocity magnitudes of 0.01 to 0.02 m/s which were close to the resolution of the ultrasonic anemometer (0.01 m/s resolution). Additionally, the velocity magnitude randomly fluctuated and peaked approximately at 0.1 m/s. There was no consistency found in the direction of gas movement. This multi-directional gas movement indicated the mixing effect between the gas fumigant and air.

(a) (b)

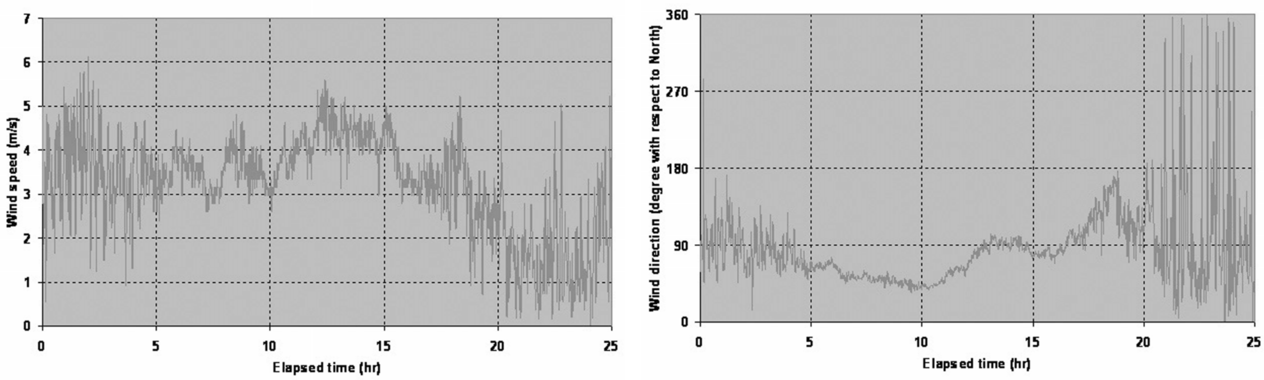


Figure 4. (a) Wind speed and (b) wind direction measured relative to the North (0 degree). 90 degree = wind from the East, 180 degree = wind from the South, and 270 degree = wind from the West.

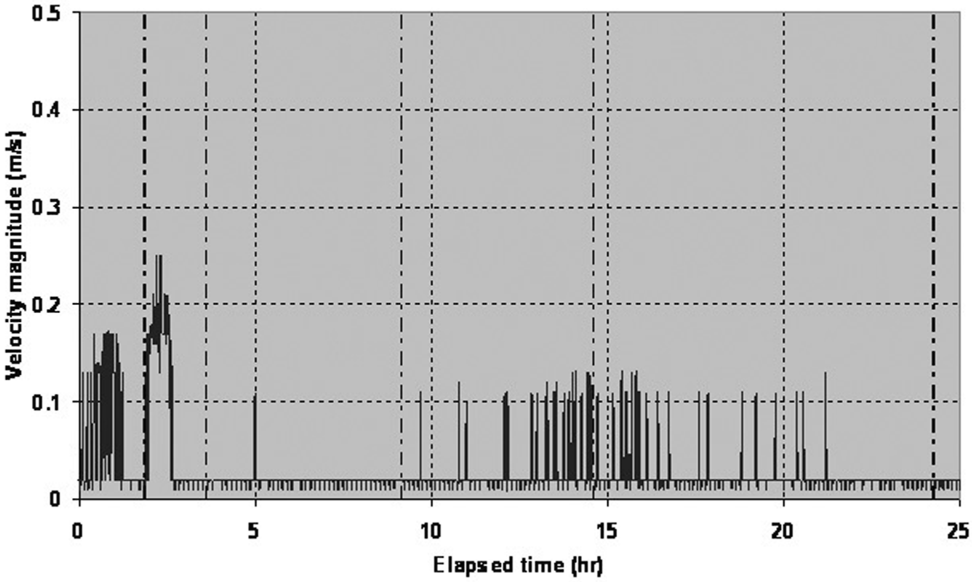


Figure 5. Velocity magnitude of the fumigant-air mixture measured on the third floor by the DAQ system. Refer to Figure 2 caption for explanation of the dash-dotted lines.

Solar radiation and wall inner surface temperature

In general, the solar radiation data looked similar to a half-sinusoidal wave (data not shown). The sensor detected no radiation between 8:00 pm of the first day and 5:30 am of the second day. On both days, the highest values (≈ 1050 and 850 Watt/m^2) were captured at solar noon which at this mill location occurred at 1:30 pm local time. During the fumigation, the wall temperature on the lower floors were lower than those on the higher floors (data not shown). The inner surface temperature of all walls on the first floor ranged between 28 and 31 °C. The wall temperature on the second, third, and fifth floors ranged between 31 and 36 °C. For the sixth floor walls, the temperature varied between 33 and 38 °C.

Fumigant concentrations

Concentration readings of the odd numbered monitoring locations and those of the even numbered monitoring locations are plotted in Figures 6a and 6b, respectively. During the introduction period (i.e, the first and second ProFume® releases), the concentrations on each floor rapidly increased. Although the concentrations at each location peaked at a different value, in general the locations on the same floors had maximum concentrations of similar magnitudes. The concentrations on the lower floors peaked at greater values and vice versa. When the circulation fans on the second, third and fourth floors were first turned off, there were still substantial differences in the concentrations among the floors. However, the remaining fans operating and the natural convection currents were sufficient to create a uniform gas distribution. Around the sixth hour, most areas in the mill had relatively the same concentration. After this hour, the differences in the concentration readings of most locations were within 5 g/m^3. The initial uniform concentrations measured by the Fumiscopes monitoring the odd and even locations (except the sixth floor) were approximately 50 g/m^3 and 58 g/m^3, respectively. Afterwards, the concentrations at most locations started to decay at approximately the same rate. However, the concentrations at the M5_1, M5_3 and M5_4 locations equilibrated with the concentrations on the lower floors at 36, 42 and 48 g/m^3, respectively. The cause of this observation could not be identified.

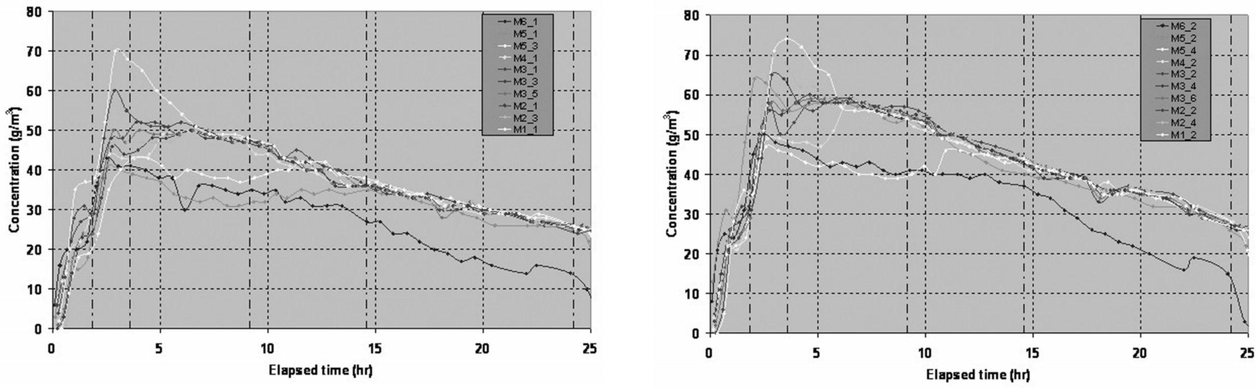


Figure 6. ProFume® concentrations in units of g/m^3 measured during the actual fumigation at (a) odd numbered locations and (b) even numbered locations. Refer to Figure 2 caption for explanation of the dash-dotted lines.

Half-loss time of fumigation

The loss of fumigant concentration can be modeled by homogeneous first-order differential equations which have solutions in the following form:

$$C_t \frac{C_i}{e^{t}} \quad \text{or} \quad C_t \frac{C_i}{2^{\frac{t}{HLT}}} \qquad (1)$$

where C_t = current concentration (g/m^3) at time t, C_i = initial concentration (g/m^3), t = exposure time (hours), t = characteristic time constant (hours), and HLT = t ln(2) (hours). The decaying sections of the concentration curves of the first five floors were almost identical, while the curves of the sixth floor indicated a different leakage trend. Based on the amount of fumigant being released, the theoretical maximum concentration level on the sixth floor should have been close to those of the other floors. In general, the gas concentration on this floor was always lower than those of the other floors by 10 to 20 g/m^3. This implies that the fumigant leakage rate of the sixth floor was higher than those of the other floors. When fitting the concentration curves between the fourteenth and twenty-second hours with Equation 1, the M6_1 and M6_2 locations presented HLTs of 7.4 (R^2 = 0.98) and 6.6 (R^2 = 0.98) hours, respectively, which were substantially lower than the HLTs of the other locations (Table 1).

Table 1. Parameter estimates of the concentration data of the first five floors when fitted using Equation 1.

Location	C_i	t	HLT (hr)	R^2
		Odd numbered		
M5_1[1]	50.3	22.7	15.7	0.94
M5_3[2]	47.4	29.7	20.6	0.96
M4_1	48.9	25.3	17.5	0.99
M3_1	49.6	24.7	17.1	0.98
M3_3	48.9	25.8	17.9	0.98
M3_5	49.7	24.3	16.8	0.97
M2_1	50.7	23.5	16.3	0.98
M2_3	49.7	24.4	16.9	0.99
M1_1	50.4	25.0	17.4	0.99
AVG	49.5	25.0	17.4	
		Even numbered		
M5_2	56.8	24.8	17.2	0.98
M5_4[3]	54.5	29.2	20.3	0.97
M4_2	57.7	25.5	17.7	0.99
M3_2	58.9	24.1	16.7	0.99
M3_4	58.9	23.1	16.0	0.95
M3_6	58.8	23.7	16.4	0.97
M2_2	59.9	23.6	16.4	0.96
M2_4	59.7	23.3	16.1	0.97
M1_2	56.9	25.1	17.4	0.97
AVG	58.0	24.7	17.1	

[1] Fitted with the readings between the sixteenth and twentieth hours.

[2] Fitted with the readings between the twelfth and twentieth hours.

[3] Fitted with the readings between the eleventh and twentieth hours.

In spite of the variations in the environmental conditions and the use of two different Fumiscopes, the HLTs for all monitoring locations (except the sixth floor) were similar when fitting the concentration data between the seventh and twenty-second hours with Equation 1. Table 1 summarizes the resulting parameter estimates. Most HLTs were between 16 and 18 hours with coefficients of determination, R^2, above 0.95. The average HLTs of the odd and even monitoring locations were 17.4 and 17.1 hours, respectively. Thus, it was concluded that for this particular fumigation the HLT was constant at 17 hours.

Conclusions

The pressure data indicated that the hydrostatic pressure in the commercial flour mill was dominated by the barometric pressure of the environment. Sealing of the structure did not create sufficient air-tightness to cause a pressure build-up inside the structure due to the introduction of the fumigant. Operation of the circulation fans did not contribute to the fumigant leakage because it had no effect on the hydrostatic pressure in the mill. However, the circulation fans aided in reducing the time to achieve uniform fumigant concentrations throughout the mill. The differences in the concentration readings of most locations were within 5 g/m^3 during the concentration decay period. A relatively constant HLT of 17 hours was reached for the first five floors. The sixth floor, which was not as air-tight as the other floors, yielded a substantially lower HLT ($\approx$ 7 hours).

Acknowledgments

This study was funded by the USDA-CSREES Methyl Bromide Transition Program under project grant 2004-51102-02199 “Fumigation Modeling, Monitoring and Control for Precision Fumigation of Flour Mill and Food Processing Structures.” The cooperation, input and help of Mr. John Mueller, Mr. David Mueller, Mr. Peter Mueller and the staff of Fumigation Service & Supply Inc., Indianapolis, Indiana has been greatly appreciated throughout this project. The cooperation of Dr. Suresh Prabhakaran, Mr. Marty Morgan and other staff at Dow AgroSciences, Indianapolis, Indiana, as well as the staff of several flour mills is also acknowledged.

References

Chayaprasert, W., Maier, D.E., Ileleji, K., Murthy, J., 2005. Predictions of fumigant movement and half-loss time of structural fumigation in a flour mill using CFD simulations. Paper No. 05-3079, ASABE, St. Joseph, Michigan, USA.

Chayaprasert, W., Maier, D.E., Ileleji, K., Murthy, J., 2006. Development of CFD Structural Fumigation Models for Predictions of Fumigant Movement and Half-Loss Time. Paper No. 06-3001, ASABE, St. Joseph, Michigan, USA.

Cheong, K.W.D., Djunaedy, E., Poh, T.K., Tham, K.W., Sekhar, S.C., Wong, N.H., Ullah, M.B., 2003. Measurements and computations of contaminant’s distribution in an office environment. Building and Environment 38, 135-145.

Gilham, S., Deaves, D.M., Woodburn, P., 2000. Mitigation of dense gas releases within buildings: validation of CFD modelling. Journal of Hazardous Materials 71, 193-218.

Key Chemical and Equipment., 2006. Fumiscope manual. Available at: www.fumiscope.com. Accessed 15 June 2006.