Improving the Structural Fumigation Process – Possibilities and Technologies

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Focus on ProFume and IPM Tactics in the Food Industry
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Structural Fumigation Modeling

Introduction

- MB is being phased-out globally
- What can be done to…
  - accelerate reduction of MB use in food processing structures?
  - improve efficacy of MB alternatives such as SF and heat?
- In 2004, a research project was initiated at Purdue University and industry collaborators with the aim to develop a comprehensive analysis tool, and an automatic monitoring and decision support system for structural fumigation
- In 2008, a second project was initiated at Kansas State University in collaboration with Purdue University, USDA-ARS GMPRC and industry collaborators to improve the structural fumigation process and advance the adoption of methyl bromide alternatives in the grain-based food processing industry
- Both projects were supported by USDA-CSREES Methyl Bromide Transition Grants as well as industry funds
- This presentation summarizes our findings and explores several possibilities and technologies to improve the structural fumigation process

Structural Fumigation Modeling

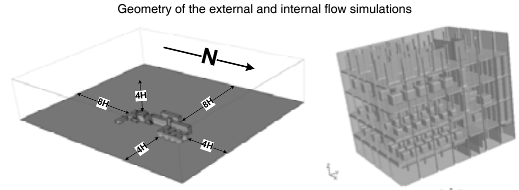
- Facility A was selected as the reference structure
- Computational Fluid Dynamics (CFD) software, Fluent®, was used to construct two flow models
  - A sub-model of the flow outside the reference mill for predicting pressure profiles on the structure's walls created by wind speed & direction
  - A sub-model of the fumigation process inside the mill
  - Assuming no sorption
- Goal
  - To predict concentration data similar to that observed during the actual fumigation, given the same environmental conditions and fumigation practices

Fumigation Experiments

Structural Fumigation Modeling

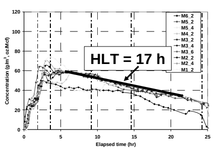
- The average stagnation pressures that would have occurred on the walls during the fumigation period were estimated by the external flow model
- The average stagnation pressures were used as boundary conditions of the internal flow model

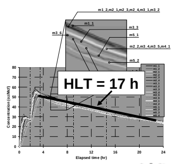
Geometry of the external and internal flow simulations



Structural Fumigation Modeling

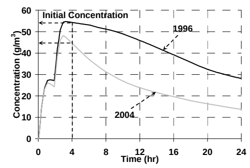
- Model slightly underpredicted concentration levels
  - ≈ 5 g/m^3 on average
- However, the HLT of the simulated concentration curves was identical to the HLT of the actual mill (17 hr)
- Due to the underpredicted concentration, the achieved Ct product was underpredicted by 10.5%
  - actual Ct = 950 vs. predicted Ct = 850 $g\text{-}hr/m^3$

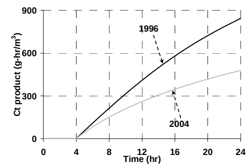




Results

- Initial concentration was almost 20% different (54.3 → 44.6 g/m^3)
- HLT was more than 100% different (10.7 → 23.3 hours)
- Ct product was more than 70% different (476 → 840 $g\text{-}hr/m^3$)
- If the HLT of the 2004 fumigation was estimated based on the 1996 concentration record, the 2004 fumigation could potentially be a failure due to the lack of sufficient gas injection





Model Application: 11 year fumigations

- To evaluate the effects of multi-year weather conditions (1996 – 2006) on the gas leakage rate (i.e., HLT) and the concentration×time (Ct) product during structural fumigation in the mill
- 11 simulations with the same fumigation period of different years (1996 – 2006): 12:00pm July 4th to 12:00pm July 5th
- Hourly historical weather data recorded at a nearby airport: wind speed, wind direction and ambient temperature
- Every other parameter was assumed the same (e.g., building air-tightness, amount of injected fumigant, internal temperature)
- 2,500 lb of sulfuryl fluoride (SF) for each fumigation

Summary of Results

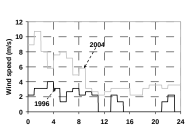
- In general, higher wind speeds and larger temperature differences → higher leakage rates
- Fumigant leakage rate was primarily a function of the combination of wind speed, wind direction and temperature difference

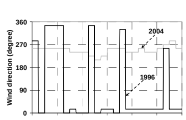
Year	Init. Conc. (g/m^3)	HLT (hr) [R^2]	Ct ($g\text{-}hr/m^3$)	Wind Spd. (m/s)		Wind Dir. (degree)		Ambient Temp. (°C)	
				Avg.	S.D.	Mode	# of hrs.	Avg.	S.D.
1996	54.3	23.3 [0.94]	840	1.5	1.3	0	21	20.9	4.4
1997	49.7	13.6 [0.99]	633	4.0	1.6	315	16	16.2	3.5
1998	53.4	18.2 [0.99]	757	4.4	1.3	0	11	23.3	2.9
1999	49.6	13.2 [0.97]	598	4.0	1.6	225	20	28.3	3.6
2000	52.8	19.6 [0.99]	752	2.1	1.9	0	10	24.4	2.5
2001	52.5	15.5 [1.00]	696	3.5	0.9	270	14	22.5	3.5
2002	51.2	19.8 [0.99]	730	3.2	0.8	45	8	29.1	3.3
2003	48.5	12.5 [0.97]	571	5.1	2.6	225	7	25.2	4.9
2004	44.6	10.7 [0.95]	476	4.7	2.4	270	14	23.6	3.7
2005	49.7	15.9 [1.00]	658	4.1	1.3	0	6	25.5	4.1
2006	49.7	15.7 [0.97]	672	4.8	1.4	45	10	22.4	3.1
Avg.	50.5	16.2	671						
S.D.	2.7	3.7	101						

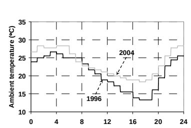
Results

- Historical weather data for the years in which the fumigation had the lowest (1996) and highest (2004) leakage rates
- Year-to-year variations in weather conditions could be substantial

		1996	2004
Wind spd. (m/s)	Min.	0	2
	Max.	4	11
	Avg.	1.5	4.7
Wind dir.	Mode	North	West
Temp. (C)	Min.	13	18
	Max.	27	28
	Avg.	20.9	23.6







Conclusions

- Even though sealing quality was maintained the same, year-to-year weather variations had a significant effect on fumigant leakage rates, causing variations in initial concentrations (45 – 54 g/m^3), HLTs (11 – 23 hr) and Ct products (476 – 840 $g\text{-}hr/m^3$)
- Non-optimized fumigation process
  - Overdose in the case of underpredicted HLT
  - Intermittent additional injection in the case of overpredicted HLT
- In order to optimize the fumigation process, using past fumigation data as the primary means for evaluating the effectiveness of temporary structural sealing quality and predicting HLT is ***not*** adequate
- Predictions of HLT and thus fumigation performance should incorporate quantifiable sealing effectiveness and weather information for the planned fumigation period

Model Application: Leakage rate, SF vs MB

- Is there any difference in the leakage rate between SF and MB?
- Repeat the 11-year simulated fumigations with MB
  - Same sealing quality and fan placement
  - Same weather conditions
  - Half of the fumigant amount used in the SF fumigations

Model Application: Effect of sealing quality

- Three levels of sealing quality were verified by actual pressurization tests at the Hal Ross Mill
- A CFD model of the Hal Ross Mill was built and specified gas-tightness at these three levels
- A sensitivity analysis study was conducted using fumigation simulations of this model
  - Assuming 100 g/m^3 of initial concentration
  - Assuming fixed wind speeds without buoyancy force

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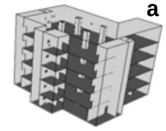
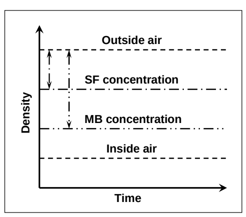


Results

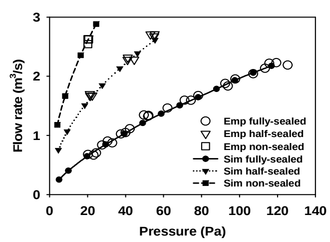
- Leakage rates of MB appeared higher than those of SF
  - HLT of MB was ≈ 2 hr lower than that of SF on average
  - Differences in gas concentration levels caused different stack effects
  - The outside air density was higher than the inside air density → Lower gas concentrations resulted in a greater stack effect

Year	MB Init. Conc. (g/m^3)	MB HLT (hr)	MB Ct (g-hr/m^3)	SF Init. Conc. (g/m^3)	SF HLT (hr)	SF Ct (g-hr/m^3)
1996	27.3	16.8	360	54.3	23.3	840
1997	24.0	12.1	280	49.7	13.6	633
1998	27.5	16.4	359	53.4	18.2	757
1999	22.4	12.1	275	49.6	13.2	598
2000	25.5	17.4	355	52.8	19.6	752
2001	26.0	14.4	328	52.5	15.5	696
2002	25.2	19.5	358	51.2	19.8	730
2003	21.4	11.3	256	48.5	12.5	571
2004	18.2	9.8	208	44.6	10.7	476
2005	23.5	14.8	304	49.7	15.9	658
2006	25.1	14.3	310	49.7	15.7	672
Avg.	24.2	14.4	309	50.5	16.2	671
S.D.	2.7	2.9	50	2.7	3.7	101



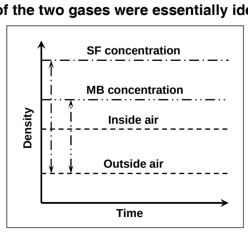
Results

- At any applied pressure, the leakage flow rate was always lower with better sealing quality



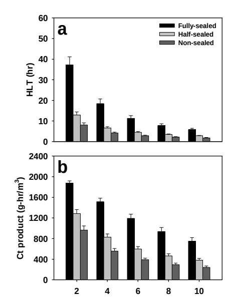
Results

- Not an indication that MB leaks more rapidly than SF
  - When wind dominates, the stack effect may be insignificant
  - If the outside air density is lower than the inside air density, higher gas concentrations will yield a greater stack effect
- Additional simulations showed that when applying the same fumigant amount, HLTs of the two gases were essentially identical



Results

- HLT is a function of both wind speed and sealing quality
- Proper sealing increases HLT 3 – 4 folds from the non-sealed to the fully-sealed building
- HLT decreased several folds when wind increased from 2 to 10 m/s
  - Regardless of sealing quality, fumigation under severe weather should be avoided

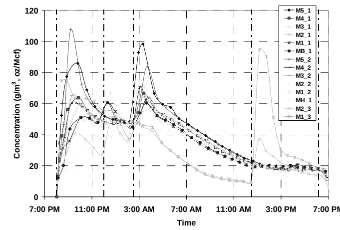


Other Applications

- The models can be used to predict fumigation characteristics such as fumigant movement paths, concentration distributions, and leakage rate
- The effects of fumigation variables such as wind speed and direction, capacity and placement of circulation fans, and fumigant release time on the efficacy of the fumigation process can be quantified
- The simulations will provide insight into understanding the dynamics of the structural fumigation process and help fumigators to correctly determine the dosage amount, which in turn will yield increased efficacy and more successful fumigation jobs
- Models could be used to quantify fumigant dispersal into the environment during fumigation and during aeration

Importance of Circulation Fans

- Facility B
- No fan
- Two monitoring points per floor
- Volume = 6,666 m^3
- Differences in concentrations between floors were greater than 5 g/m^3



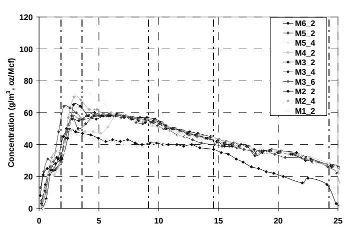
Key Factors To Improving Structural Fumigation

Importance of Circulation Fans

- Despite the fact that Facility A is more than four times larger than Facility B, the fumigant in Facility A was more uniformly distributed because of the circulation fans
- Circulation fans dominate gas movement and thus are most important for achieving uniform distribution
  - The optimum gas distribution can be achieved by proper sizing and placement of circulation fans
- Currently, our CFD models are being used to evaluate the effects of capacities and placements of circulation fans on gas distribution
  - This would allow specification of the minimum/optimum fan capacity/number required for a particular fumigation volume

Importance of Circulation Fans

- Facility A
- One fan per floor
- Two monitoring points per floor
- Volume = 28,317 m^3
- Differences in concentrations between floors were within 5 g/m^3



Importance of Sealing

- The fumigation process can be modeled by:

$$\frac{C}{C_{init}} = \frac{1}{2^{\frac{t}{HLT}}}$$

- The theoretical Ct product can be described by:

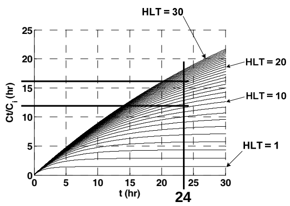
$$\frac{Ct}{C_{init}} = \frac{HLT \times (1 - 2^{-\frac{t}{HLT}})}{\ln(2)}$$

- Although it has not yet been quantified, HLT is the direct function of sealing quality

Importance of Sealing

- At any given exposure time the fumigation process with a higher HLT…
  - results in a higher Ct product value for the same fumigant use
  - results in lower fumigant use for the same Ct product

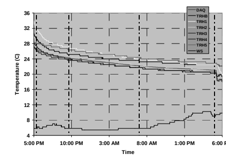
Normalized Ct product plot with HLT varied between 1 and 30 hours



Importance of Fumigated Space Temperature Monitoring

- For any fumigant the Ct product required to kill a particular insect species and life stage varies as a function of the temperature of the fumigated space
- Current fumigation practice assumes that the fumigated space temperature remains constant to determine dosage rate (Ct product) while fumigation is a rather dynamic process
- The temperature inside a sealed structure can decrease by as much as 9°C

Temperature decreases on the six floors of Facility C during fumigation



Importance of Sealing – Fumigation Experiments

Facility		Ambient Conditions			Inside Conditions		Fumigation Results				
#	Size (m^3)	Temp (°C)	RH (%)	Wind Speed (m/s)	Temp (°C)	RH (%)	Fumigant	Exposure Time (hr)	Estimated HLT (hr)	Achieved Ct ($g\text{-}hr/m^3$)	Fumigant Usage (kg)
		19 - 30	40 - 92	0 - 6	33 - 37	28 - 42	SF	24	17 - 20	612 - 1014	1361
A	28,317	21 - 31	35 - 97	1 - 23	32 - 37	25 - 40	SF	23.5	6	427 - 554	1077
		21 - 33	23 - 64	0 - 8	30 - 40	24 - 40	SF	22.5	10	520 - 680	1077
B	6,666	15 - 30	35 - 75	0 - 7	30 - 36	31 - 42	SF	23.5	5 - 6	507 - 907	N/A
		10 - 23	53 - 98	1 - 6	29 - 34	35 - 45	SF	22	5 - 6	775 - 986	680
		6 - 10	81 - 96	1 - 8	20 - 32	24 - 37	MB	23.5	10 - 11	150 - 310	315
C	4,336	15 - 22	78 - 99	0 - 6	24 - 32	31 - 51	SF	23	20 - 22	788 - 1128	397
		11 - 22	21 - 71	0 - 9	25 - 30	22 - 35	SF	24	6 - 8	873 - 1346	624

- When Mill A's HLT increased from 6 to 10 h, the achieved Ct product increased ≈ 20% (given the same fumigant usage)
- When Mill C's HLT decreased from 20 to 8 h, the fumigant usage increased by 50% (achieving approximately the same Ct product)

Importance of Fumigated Space Temperature Monitoring

- Assuming HLT = 12 hr, exposure time = 24 hr and volume = 100 m^3
  - At 30°C, required SF = 4.6 kg
  - At 21°C, required SF = 10.7 kg
- Temperature monitoring should be incorporated as a best management practice in every fumigation management plan

"Relative" Ct products ($g\text{-}hr/m^3$) of sulfuryl fluoride (SF) required to kill eggs of red flour beetle (RFB), rice weevil (RW) and Indianmeal moth (IMM)

	Temperature (°C)											
	20	21	22	23	24	25	26	27	28	29	30	31
RFB	1.00	0.96	0.91	0.87	0.82	0.77	0.70	0.63	0.56	0.48	0.41	0.41
IMM	1.00	0.94	0.89	0.83	0.78	0.72	0.75	0.77	0.79	0.81	0.84	0.84
RW	1.00	0.93	0.85	0.78	0.71	0.63	0.61	0.58	0.56	0.53	0.51	0.51

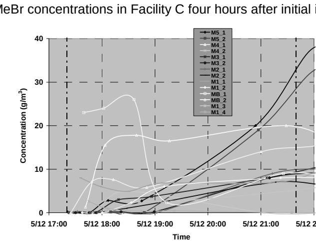
Facility Pressurization Test

- Allows for quantification of sealing quality and thus gas leakage ahead of fumigation
  - Determine the predicted HLT
  - Raise predicted HLT to target HLT with extra sealing if too low
  - Calculate precise gas dosage
- Monitor fumigation to track measured HLT against target HLT
  - Correct fumigation problems in real time
- Available equipment and standard test method

Importance of Fumigant Gas Monitoring

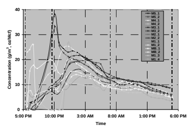
- In one of our experiments, an unforeseen problem was detected early only because of continuous gas monitoring

MeBr concentrations in Facility C four hours after initial injection



Importance of Fumigant Gas Monitoring

- During the first four hours, fumigant (MeBr) concentrations were unexpectedly low at most locations
  - Initial MeBr introduction was 181 kg (400 pounds) and approximately 40 g/m³ concentration was expected
- At the fourth hour, it was discovered that a small ventilation exhaust fan was unintentionally left operating
  - Additional 102 kg (225 pounds) of MeBr were added
- Without continuous gas monitoring, the fumigation would have been a total and completely undetected failure
  - Many millers licensed to fumigate with MeBr but no requirement to monitor



Superposition

- Quadratic superposition method
  - described in ASHRAE Handbook
  - used by the HVAC industry to quantify air infiltration in houses for energy saving and in-door air quality purposes

$$Q = \sqrt{Q_s^2 + Q_w^2} = \frac{A_L}{1000}\sqrt{C_s \Delta t + C_w U^2}$$

Total leakage rate (Q); Leakage due to stack effect (Q_s); Leakage due to wind effect (Q_w); Equivalent leakage area (A_L); Stack coefficient (C_s); Temperature difference (Δt); Wind coefficient (C_w); Wind velocity (U)

Relating Sealing Quality to HLT

Superposition: Relating to HLT

$$HLT = \frac{V \ln(2)}{Q\,3600}$$

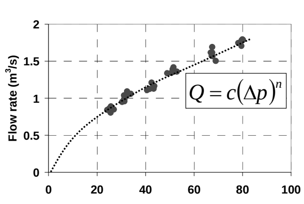
Fumigated volume (V); Total leakage rate (Q)

?

$$Q = \frac{A_L}{1000}\sqrt{C_s \Delta t + C_w U^2}$$

Pressurization Test

- Standardized pressurization test: ASTM, CGSB, ISO
- Qualitative indication of sealing quality
  - Correlation between air leakage and pressure acting on the building



Superposition: Determining Parameters

- Determined the equivalent leakage area:

$$Q = c(\Delta p)^n \dashrightarrow A_L = 10000\,Q_r \frac{\sqrt{\rho / 2\Delta p_r}}{C_D} \dashrightarrow A_L = \frac{10000c}{C_D}\sqrt{\frac{\rho}{2}}\,\Delta p_r^{(n-0.5)}$$

- Determined the stack and wind coefficients under fixed environmental conditions:

$$Q = \frac{A_L}{1000}\sqrt{C_s \Delta t + C_w U^2} \quad \dashrightarrow \quad Q = \frac{A_L}{1000}\sqrt{C_s \Delta t}, \qquad Q = \frac{A_L}{1000}\sqrt{C_w U^2}$$

Key Points

- Accurate HLT prediction → Benefits to optimizing structural fumigation
- Extensive experimental study is needed
  - Quadratic superposition method was developed specifically for application in residential houses
  - Superposition method already includes a set of inherent assumptions (e.g., pressure distribution, leakage characteristic, and assumed values of parameters)
  - HLT prediction accuracy relies on estimations of the stack and wind coefficients → These coefficients of each structure are unique

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Benefits of Comprehensive Monitoring System

- Automatic direct data entry for fumigation decision support software such as Fumiguide
  - More accurate HLT and Ct product calculations
  - Better fumigation records for future injection/monitoring/circulation fan/sealing plans
- Possibilities for new fumigation control strategies
  - Incorporation of fumigated space temperature for dynamic achieved Ct product calculation
  - HLT and Ct predictions based on real-time and forecast external and internal environmental conditions
- Remote operator access via cell phone and/or internet
  - Operator can leave site and manage multiple system locations
  - Auto updates and alarms: unexpected gas loss or severe weather
- Easy-to-setup monitoring system
  - Less labor needed
  - Faster fumigation preparation and cleanup: reduced production down time

→ Cost and product stewardship program benefits

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Automated Monitoring and Decision Support System

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Summary – Improving Structural Fumigation

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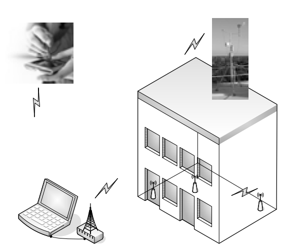
Ideal Comprehensive Monitoring System

- Automated system
- Gas concentration acquisition
  - Wireless concentration sensing modules at multiple mill locations
- Environmental data acquisition
  - Wireless mill T/RH sensors
  - Wireless weather station with wind speed & direction, T and RH, or internet forecast from a nearby weather station
- Laptop with cell phone/broadband modem and wireless local data network card
- Fumigation decision support software



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Summary – Improving Structural Fumigation

- Circulation fan efficacy, mill temperature, wind speed & direction, sealing efficacy, and fumigant sensor accuracy significantly impact fumigation success
- Modeling the fumigation process helps to quantify the effect of these parameters on fumigation success
- Circulation fans aid in the uniform distribution of the fumigant
  - Natural convection and diffusion are much slower processes
- Mill temperature has a direct effect on needed Ct product
  - Decrease with time needs to be monitored to adjust Ct and finetune needed fumigant amount to achieve insect kill
- Wind speed & direction and temperature difference affect fumigation gas leakage and therefore HLT and fumigation success

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Summary – Improving Structural Fumigation

- Sealing directly improves HLT
  - As HLT increases from 10 to 20 h, Ct increases (and needed fumigant use decreases) by up to 40%
- Pressurization testing should be explored/utilized to check sealing efficacy before fumigation starts
  - Allows for HLT prediction, needed sealing improvements, and setting of a target HLT
- Monitoring of each fumigation should occur in real-time
  - Changes in actual HLT can be tracked against target HLT
- Accuracy of fumigant sensor directly affects over- or underdosing and thus cost of fumigation
  - 10% accuracy results in 11% dosage variability
  - 50% accuracy results in 55% dosage variability

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  - Dow AgroSciences LLC, Indianapolis, IN
  - Industrial Fumigant Company, Kansas City, KS
  - Several flour mills

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