Quantifying grain storage structure leakage by testing effects of environmental conditions on pressure loss

Carol Jones*, Taylor Conley

Oklahoma State University, 216 Ag Hall, Stillwater, OK 74078,
* corresponding autor: jcarol@okstate.edu
DOI 10.5073/jka.2018.463.124

Abstract

A major concern in grain storage and management facilities is the effective control of insects and pests that reside in stored grain. Currently, the best studied method of subduing these insects is fumigating the grain bins with phosphine. However, many grain storage insects have developed a resistance to phosphine due to its misuse over the years, partially due to bin leakage, leading to minimum pest control in grain and increased product damage. The first step in managing the issue of fumigant leakage is by identifying environmental conditions that may impact the bins' total air loss, and ultimately, fumigant loss. One way to quantify the leakage potential of a structure is to perform pressure tests. Data collected from these tests statistically quantify the significance of atmospheric conditions on bin leakage, as well as quantify leakage area in the bin. These tests were performed on a 500 bushel grain bin filled with canola seed, sealed with plastic sheeting and Gorilla duct tape. A PVC pipe "arm" and shop vacuum (Shop-Vac® 5-gallon 6-Peak HP) contraption was designed for pressure application. Constant pressure testing methods were performed to collect data for calculations of leakage area. Tests were repeated in varying environmental conditions. Data analysis included performing single sample t-tests to determine significance of environmental conditions, as well as using previously established relationships to quantify predicted leakage area in each scenario. It was concluded that atmospheric conditions significantly affect gas leakage from structures ($p < 0.001$), so pressure test conditions should match fumigation conditions for an accurate initial fumigant dosage. Constant pressure tests accurately predict equivalent leakage area of bin, with areas demonstrating a variance of 3.4×10^{-5}. Future tests to improve fumigating processes could include relationships between phosphine concentration and the leakiness of the bin, as well as automated constant pressure testing devices.

Keywords: Phosphine resistance, fumigation, grain storage, leakage area, pressure testing.

1. Introduction

With populations across the world continuing to grow at an exponential rate and increasing life expectancies, it is inevitable that food production and storage will need to be continuously innovated to meet this growing need. One method that has been used for centuries is storing agricultural products, such as grain, as long as possible to ensure they are available when needed after harvesting season. Grain is known to last for long periods of time in storage facilities after drying due to lower moisture content. Nevertheless, it is still susceptible to damage from pests. The most effective way of controlling these pests is by utilizing fumigants and chemicals to eradicate their populations before the grain incurs too much damage. Over the years, the public has developed a growing concern regarding their foods, especially unfamiliar chemicals. Despite adverse public response, some chemicals, such as fumigants (i.e., phosphine, methyl bromide, etc.), are necessary to keep food products safe from disease-carry pests, specifically in stored products such as grain. These pests are not just detrimental to the fate of stored grain, but they have also proven extremely difficult to eradicate from the storage bin due to their resistance to most toxic chemicals. Grain pests include: *Rhyzopertha dominica* (F.), commonly known as the lesser grain borer; *Sitophilus oryzae* (L.), the rice weevil; *Tribolium castaneum* (Herbst.), also known as the red flour beetle; and *Oryzaephilus surinamensis* (L.), the saw-toothed grain beetle. While there are many other stored product insect pests, the aforementioned are four of the more commonly studied species. Not only do the insects damage the grain, they also leave waste product in the grain, which quickly diminishes the quality of grain. If left untreated, these insects have the ability to cause detrimental damage on the grain they are infesting.

One of the most common and cost effect methods of eliminating insects from grain is through fumigation. Attempts to eradicate pests through fumigation involve introducing a chemical toxic to the pests, such as phosphine or methyl bromide. However, due to its ozone-depleting properties, methyl bromide has been banned as a fumigant in developed countries. Sulfuryl fluoride is a fumigant that is gaining popularity, but phosphine is still the most commonly used fumigant worldwide due to its low cost and minimal residue on treated grain. Moreover, due to incomplete fumigations using phosphine, grain storage pests have developed resistance (Daglish, 2004; Lorini et al., 2007; Price, 1984). A cause of incomplete fumigation is leakiness in grain storage structures. One way to predict the leakage area of grain storage structures prior to fumigation is by performing pressure tests, such as half loss time or constant pressure tests. Half loss pressure tests, also known as half loss time (HLT) have been used extensively in many studies (Chayaprasert et al., 2012), but it has been proven to not be the most reliable method of predicting the estimated leakage area from the bin (Mann et al., 1999). In this study, the constant pressure testing method is utilized since it has potential to be a more reliable method of pressure testing. It is also known that there is an expected correlation between atmospheric conditions, such as wind speed, temperature, and relative humidity, but previous studies have not used field trial data to statistically quantify this correlation (Chayaprasert et al., 2009). Therefore, this study will focus on using constant pressure testing methods to determine whether atmospheric conditions significantly affect gas leakage from grain storage structures, as well as estimating the leakage area using constant pressure data to predict a more accurate phosphine dose to reduce development of insect resistance.

2. Materials and Methods

Initial bin modifications

A selected grain storage bin at Oklahoma State University's Stored Product Research and Education Center (SPREC) was modified prior to testing. Modifications included drilling a hole and developing an extension arm that allowed for a shop vacuum hose to connect to the headspace of the bin (Fig. 1). The selected grain bin was a 500 bushel (12.5 metric tonnes approximately) steel bin bolted to a concrete slab and filled with canola seed. External valves correlated with various depths of the bin were already installed, and were used in the experiments to measure gauge pressure. To create an opening for an airflow source to perform pressure testing, a 1 ½ inch hole was drilled into the headspace of the bin. A 1 ½ inch PVC pipe fitting was then sealed into the hole using silicone caulking. To keep out moisture and other atmospheric conditions between testing, a cap was placed over the fitting. In order to create a path for air to flow from a pressurization source (shop vacuum) to the bin, a 90° elbow, which connected to the fitting in the headspace, was attached to one end of a three foot section of 1 ½ inch PVC pipe. A 60° PVC elbow was attached to the other end to connect a seven foot section, which went down the outside wall of the bin. To control airflow going into the bin (for the constant pressure/variable flow testing), a PVC ball valve fitting was attached to the other end of the seven foot PVC section. All PVC connections were made using PVC primer and cement. The arm was utilized to pressurize the bin by sealing the end of the shop vacuum hose to the ball valve using Gorilla duct tape.

Fig. 1 Extension arm created from PVC pipe to extend down side of bin for pressurization using shop vacuum

Fig. 2 HOBO Wind Speed Smart Sensor attached to top of pole to measure wind speed free from obstruction

Constant pressure tests with varying weather conditions

In order to correlate grain bin leakage with weather conditions, added instrumentation was installed to measure relative humidity (r.h.) and temperature inside and outside of the bin, and wind speed outside of the bin. To measure wind speed, an Onset HOBO® Wind Speed Smart Sensor was attached to a 15 foot pole (Fig. 2) near the grain bins and above obstructions. An Onset HOBO® micro station data logger was connected to the wind speed sensor to record wind speed data. Temperature and r.h. were measured using Onset HOBO® Pro v2 temp/RH sensors. One of the sensors was placed outside next to the bin according to manufacturer's directions. The second sensor was taped to the inside entry latter of the bin with Gorilla duct tape. All sensors were launched using HOBOware v. 3.7.8 and were programmed to take measurements once every 30 seconds starting at the time of each test.

There were four varying weather conditions in which the constant pressure tests were performed: hot and windy, hot and still, cold and windy, and cold and still. Conditions for each test can be seen in Table 1. Constant pressure tests were conducted by first resealing the aeration fan intake and the hatch entrance with tape and double-layered plastic sheets. Other leakage-prone areas that were previously sealed with tape were re-sealed prior to testing. Next, the extension arm was inserted into the headspace of the bin, and the shop vacuum hose was securely sealed to the ball valve. A Pitot tube was inserted upstream of the ball valve in the extension arm, and worked in conjunction with a Fluke 922 Airflow Meter to measure the air velocity going into the bin. Testing began by turning the shop vacuum on with the ball valve 100% open, and monitoring the U-tube manometer until a constant pressure was reached. As soon as the pressure stabilized, a timer was started and the air velocity was measured and recorded. For each varying weather condition constant pressure test, five trials were performed at each ball valve position, where air velocity and pressure data were collected once every thirty seconds for 15 minutes. To create control data, additional testing was performed on a day with an average temperature of 75°F and average wind speed greater than 8 mph and less than 10 miles per hour. Five trials were performed by adjusting the ball valve position to vary the air velocity. Once the pressure readings from the inside of the bin stabilized, the pressure value was recorded as well as the average air velocity at that pressure. Ten data points representing different input air velocities and stabilized internal bin pressures were collected for each test. A total of five tests were performed to create a standard curve for predicted pressure retention at given input air velocity into the bin.

Statistical analysis of effects of weather conditions on air leakage

Single sample t-tests with a confidence interval of 0.005 were performed in order to statistically quantify the effect of varying weather conditions on gas leakage rate from bins during pressure testing and fumigation. A standard model to predict pressure retention in the bin at a given input air velocity was developed using data from the neutral conditions (average temperature of 75°F and wind speed of no less than 8 mph, and no greater than 10 mph). This model was developed by plotting the data in a scatter plot, then matching a curve to the data. The resulting equation can be useful for this particular bin to decide if the bin is sealed to a standard level according to its pressure retention with a given input velocity. However, in this case, it was used to determine if weather conditions significantly affect gas leakage rate from bins. Average velocity for each stabilized pressure was calculated in order to perform t-tests on the data collected from the varying weather conditions. T-tests compared the average velocities needed to maintain the stabilized pressures for each weather condition with the predicted pressure that should be maintained at the given velocity, taken from the developed standard model.

Determining estimated leakage area (ELA) from constant pressure tests

In a previous study by Lawrence et al. (2012), ELA was calculated using constant pressure tests on a flour mill using Equation 1:

$$A_L = 10{,}000 Q_r \frac{\sqrt{\rho / 2p_r}}{C_D}$$

[Eq. 1]

Where A_L is the predicted leakage area (cm^2), Q_r is the airflow rate (m^3/s), ρ is the air density (1.15 kg/m^3), p_r is the reference pressure (inch H_2O, $P_{gauge} - P_{atm}$ in this case), and C_D is the discharge coefficient (0.61 in this case, taken from Mann et al., 1999). This same equation was used to determine the ELA of the tested grain bin from constant pressure test data. Air flowrate was calculated by multiplying the input velocity by the diameter of the drilled hole in the headspace of the bin (0.0312 m^2). Air velocity values for Q_r that were used for this model were the average flow rates for each weather condition, and p_r was the correlated constant pressure with the air flowrate.

3. Results

Results from single sample t-tests

Weather conditions were tested on days with the conditions seen in Table 1:

Tab. 1 Weather conditions (temperature and wind speed ranges) for constant pressure test to ensure varied weather data to correlate with gas leakage rate.

Weather Condition	Avg. Wind Speed Range	Avg. Outside Temperature Range
Hot & Windy	> 10 mph	> 80°F
Hot & Still	< 8 mph	> 80°F
Cold & Windy	> 10 mph	< 70°F
Cold & Still	< 8 mph	< 70°F

After collecting data from constant pressure tests for all varying weather conditions and control data, the control data was plotted to develop a model to predict the ideal relationship between input air velocity and the maintained constant pressure at that velocity:

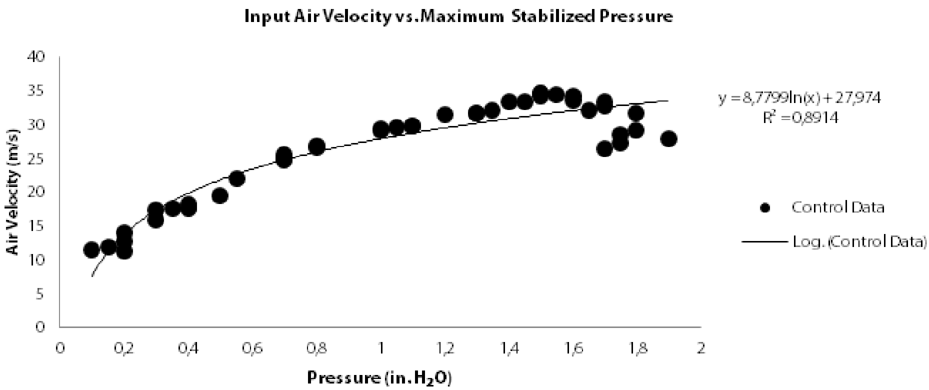

Fig. 3 Model of control data for constant pressure test.

The logarithmic equation developed from this model was used to predict the air velocity at the given constant pressure. Constant pressure test data from varying weather conditions were then compared to these predicted values. Single sample t-tests compared the predicted pressure for the average measured input air velocity with the actual maximum stabilized constant pressure maintained during the testing period. T-tests were performed for each constant pressure observed for each varying weather condition. The resulting p-values indicated if the weather factors had a significant impact on air leakage from the bin based on the maximum pressure that can be achieved in ideal weather conditions compared with maximum pressure maintained at the same input air velocity/flowrate in non-ideal conditions.

Tab. 2 Results from t-tests for constant pressure test in varying weather conditions, comparing theoretical constant pressures with actual constant pressures maintained in non-ideal weather conditions.

Weather Condition	Air Velocity (m/s)	Pressure (in.H_2O)	p-value
Hot and Windy	32.887	1.75	<0.0001
Hot and Windy	31.534	1.5	<0.0001
Hot and Windy	26.015	0.8	<0.0001
Hot and Windy	13.843	0.2	<0.0001
Cold and Windy	32.101	1.6	<0.0001
Cold and Windy	31.297	1.46	<0.0001
Cold and Windy	27.431	0.94	<0.0001
Cold and Windy	13.843	0.2	<0.0001
Hot and Still	23.489	0.6	<0.0001
Cold and Still	26.443	0.84	<0.0001

Predicted equivalent leakage areas (ELA) were also calculated using these same averages from the constant pressure test data in varying weather conditions to validate that constant pressure testing is an accurate method of estimating the ELA. Using Eq. 1, the ELA was calculated for each average input air velocity measured from the varying weather condition data.

Tab. 3 Estimated ELA for the same bin under varying weather conditions.

Q_r (m^3/s)	P_{gauge} (Pa)	A_L (m^2)
1.03	435	0.06
0.98	373	0.06
0.81	199	0.07
0.43	50	0.08
1	398	0.06
0.98	363	0.06
0.86	234	0.07
0.43	50	0.08
0.73	149	0.07
0.83	209	0.07

Average predicted ELA from this data is 0.07 m^2, with a standard deviation of 0.006 and variance of 3.4×10^{-5}.

4. Discussion

From the calculated p-values, it is evident that weather conditions significantly impact the air leakage rate from grain storage structures. This indicates not only that a higher dosage of phosphine (or other fumigant) may be needed in non-ideal conditions, but also that the atmospheric conditions at which the pressure testing takes place should match the conditions during the fumigation period for a more effective fumigation. Constant pressure testing used as a method of predicting leakage area from a grain storage structure is further validated by using the varying weather data to calculate the estimated ELA. The resulting ELA demonstrated low variance (3.4×10^{-5}), even though the air leakage rate from the same bin varied significantly with weather conditions. For future fumigations, constant pressure testing should be considered as not only a viable but more accurate method of estimating ELA than pressure HLT testing. Fumigations that utilize data from constant pressure testing to calculate the initial phosphine dose are likely to be more effective, and thus reduce the development of insect resistance to phosphine in grain storage. Future studies will automate the constant pressure test, as well as correlate initial phosphine dosage with leakage area predicted from constant pressure tests.

Acknowledgements

I would like to thank those who have provided funds for the Anderson Grant to make this research possible. I would also like to thank all others involved with this research including Mark Casada (USDA-ARS, CGAHR), Rumela Bhadra (Kansas State University), Frank Arthur (USDA-ARS, CGAHR),

Ronaldo Maghirang (Kansas State University), Brian Adam (Oklahoma State University), Dirk Maier (Iowa State University), and Samuel Cook (Kansas State University).

References

CHAYAPRASERT, W., MAIER, D.E., ILELEJI, K.E., AND J.Y. MURTHY, 2009. Effects of weather conditions on sulfuryl fluoride and methyl bromide leakage during structural fumigation in a flour mill. *Journal of Stored Products Research, 45*(1), 1-9.

CHAYAPRASERT, W., MAIER, D.E., SUBRAMANYAM, B., AND M. HARTZER, 2012. Gas leakage and distribution characteristics of methyl bromide and sulfuryl fluoride during fumigations in a pilot flour mill. Journal of Stored Products Research, *50,* 1-7. doi: https://doi.org/10.1016/j.jspr.2012.03.002

DAGLISH, G.J., 2004. Effect of exposure period on degree of dominance of phosphine resistance in adults of Rhyzopertha dominica (Coleoptera: Bostrychidae) and Sitophilus oryzae (Coleoptera: Curculionidae). Pest Management Science, 60(8), 822-826. doi:10.1002/ps.866

LAWRENCE, J., MAIER, D. E., SUBRAMANYAM, B., AND W. CHAYAPRASERT, 2012. Mill pressurization test quantifies fumigant leakage rates during sulfuryl fluoride and methyl bromide fumigation of commercial flour mills. Paper presented at the Proceedings of the Ninth International Conference on Controlled Atmosphere and Fumigation in Stored Products.

LORINI, I., COLLINS, P.J., DAGLISH, G.J., NAYAK, M.K., AND H. PAVIC, 2007. Detection and characterization of strong resistance to phosphine in Brazilian Rhyzopertha dominica (F.) (Coleoptera: Bostrychidae). Pest Management Science, 63(4), 358-364. doi: 10.1002/ps.1344

MANN, D., JAYAS, D., MUIR, W., AND N. WHITE, 1999. Predicting the gas-tightness of grain storage structures. Canadian Agricultural Engineering, 41(4), 259-266.

PRICE, N.R., 1984. Active exclusion of phosphine as a mechanism of resistance in Rhyzopertha dominica (F.) (Coleoptera: Bostrychidae). Journal of Stored Products Research 20(3), 163-168. doi: http://dx.doi.org/10.1016/0022-474X(84)90025-0

Three and Half Decades of Research on Controlled Atmosphere Storage of Grains under Nitrogen and Recent Utilization of the Technology in Nigeria

Egobude Okonkwo[1*], Michael Omodara[2], Shuaib Oyewole[2], Adaora Osegbo[1], Patricia Pessu[2], Adeola Oyebanji[2], Olufemi Peters[2]

[1]Nigerian Stored Products Research Institute, 32/34 Barikisu Iyede Street, Abule Oja, Yaba, PMB 12543, Marina, Lagos, Lagos State, Nigeria.
[2]Nigerian Stored Products Research Institute, Km 3 Asa Dam Road, PMB 1489, Ilorin, Kwara State, Nigeria.
*Corresponding author/Email: egoulu@yahoo.com
DOI 10.5073/jka.2018.463.125

Abstract

A major breakthrough of Nigerian Stored Products Research Institute (NSPRI) is in the development of Inert Atmosphere Metal Silo (IAMS) in bulk grain storage for suitability of the climate, adoption and utilization in Nigeria. This technology uses nitrogen gas to achieve a controlled atmosphere (N2-CA) or environment for the control of stored products pests infestation and damage. Achieved 100% mortality of all life adults and immature stages of stored products insect pests; inhibited mould growth, maintained biochemical composition of stored grain and germinability (85% -91%) recorded at 12 months of storage. The system has been used to effectively store white maize, groundnut, Ife brown cowpea, wheat, paddy rice and yellow sorghum for periods of 12 – 48 months. The only system that has ability to store cowpea which cannot be stored in conventional silos. Research activities commenced from laboratory trials to pilot scale and later to medium and commercial levels. Shading the IAMS top against direct sun effect with palm fronds or hood for insulation prevented moisture migration and condensation, and maintained temperature below 30 °C in stored grain. A return per unit on investment of 0.44 was recorded when utilized for storage of wheat for a period of 48 months. IAMS has economic advantages over conventional silos which require frequency of pesticides application, turning of grains to prevent caking, food poisoning and high cost of labour. The recent utilization of this technology is due to increased awareness and demands for availability of grains for food safety, quality and nutrition. IAMS is being taken up by some entrepreneurs, marketers and Landmark University, Omu-Aru, Kwara state for grain storage in Nigeria. This technology is available for use at smallholder, medium, commercial and strategic grain reserve levels. Three and half decades of application of IAMS technology in grain storage in Nigeria is discussed.

Keywords: Inert atmosphere metal silo (IAMS), Nitrogen, grain storage and quality, control of pests, utilization.

1. Introduction

The Nigerian Stored Products Research Institute (NSPRI) is one of the National Agricultural Research Institutes (NARIs) in Nigeria, being supervised by Agricultural Research Council of Nigeria (ARCN)