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VALIDATION OF MODELS FOR CONTROLLED ATMOSPHERE GAS LOSS FROM BOLTED-STEEL GRANARIES

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ABSTRACT

Predicting the loss of CA gas (CO_2) from metal grain bins caused by wind, temperature, and chimney effects will improve the efficiency and effectiveness of CA fumigation of stored grain. Two published mathematical models (Lawrence Berkeley Laboratory [LBL]; and Banks and Annis [BA]) were evaluated for their ability to predict gas loss from a galvanized steel grain bin (5.56 m diam x 6.60 m height). Experimental tests were conducted to provide validation data for the models. The effective leakage areas (ELA) of the empty bin were determined using fan pressurization tests for the bin. A CO_2-impermeable plastic sheet was attached to the inside wall at 2.5 m above the floor. This excluded the upper half of the bin including the roof, resulting in an ELA of approximately 7.69 cm^2. When the bin contained wheat, the LBL model over-predicted the wind effect by an average of 5 times the rate of the measured gas losses (CO_2 introduced as dry ice). The predicted effect of temperature on gas loss was within 1% of the rate from the bin. Error in predictions may be because the shielding and terrain coefficients used in the model do not account for the direction of the prevailing wind and are subjective for each bin site. Also, overestimation of the ELA would cause significant differences between predicted and experimental data. Predicting the rate of gas loss caused by wind with the BA model was difficult because the model was sensitive to an unknown pressure coefficient. The predicted gas loss rate for the bin due to the chimney effect was 15 times the experimental rate. Further experimental studies are needed to separate the wind, temperature, and chimney effects so that the models can be improved for estimating gas leakage losses.

INTRODUCTION

Canadian standards require a zero tolerance of live storage insects detected in commercial grain. The main insects found in stored cereals in western Canada are the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) and the red flour beetle, *Tribolium castaneum* (Herbst) (Madrid *et al.,* 1990). The application of controlled atmosphere (CA) gases to control insect infestations in grain stored in bolted-metal bins in Canada is being studied as an alternative to using chemical fumigants such as hydrogen phosphide (PH_3) (Jayas *et al.,* 1991).

The CA gases should be distributed uniformly and maintained at a specific concentration for a specific exposure time to obtain adequate insect control (Banks and Annis, 1977). However, the distribution and loss of the CA gases depend on the diffusion rate, convective flows in a structure, and bin leakage (Sherman, 1987). Convective flows may be caused by uncontrollable external factors such as wind, temperature, and chimney effects (Banks and Annis, 1984). The pressure drops across the bin wall created by these factors cause an exchange of internal gases with external ambient air through any openings in the bin wall (Sherman *et al.,* 1980). If the CA gases leak out before a uniform distribution is obtained and before the necessary exposure time has elapsed, the fumigation process will be ineffective (Alagusundaram, 1993).

In North America, two thirds of all grain storage facilities are on the farm and consist primarily of bolted galvanized-steel bins which contain many leaks (McGaughey and Akins, 1989). Sealing these bins to make them airtight is not practical, requiring extensive labour and high costs (Alagusundaram, 1993). Therefore, it is necessary to determine the loss rate of CA gases from leaky bolted-metal bins so gases may be replenished to provide an effective fumigation.

Monitoring CA gas concentration levels to determine loss rates from a specific bin is difficult because many time-consuming field experiments are required to collect reliable data. A more practical method would be to mathematically predict losses caused by environmental conditions. A model developed by Sherman and Grimsrud (1980) (Lawrence Berkeley Laboratory, LBL) predicts the infiltration-exfiltration of air from a building. This model has not been used to predict CA gas loss from bolted-metal grain bins. A mathematical model developed by Banks and Annis (1984) (BA) specifically predicts the loss rate of CA gases from treated granaries caused by changing environmental conditions. However, this model has not been tested with field data using typical grain bins in North America.

The objectives of this study were to: 1) determine the applicability of using the fan pressurization test to estimate the effective leakage area of a full-size bin; and 2) evaluate the two existing mathematical models for predicting rates of gas loss caused by wind, internal-external temperature differences, and internal-external gas density differences.

MATERIALS AND METHODS

Mathematical model parameters

The evaluated models (LBL and BA) required a number of parameters, which are specific for each bin tested (Banks and Annis, 1984; Sherman and Grimsrud, 1980). These parameters include the physical dimensions of the bins, shielding and terrain coefficients, pressure coefficients, wind speeds, temperatures, and densities.

The storage structure used in the experimental tests was a granary 5.56 m diameter with a height to eaves of 5.70 m. This bin had a coned roof with a headspace volume of 7.28 m^3. The bin was located 20 km south of Winnipeg, Manitoba.

The CA gas introduced was CO_2 as dry ice, and was calculated to produce an atmosphere of approximately 60% CO_2, <2% O_2, and 38% N_2. The density of CO_2 and the diffusion coefficient (carbon dioxide into air) at STP were 1.977 kg/m^3 and 13.8 mm^2/s, respectively (Perry and Green, 1984).

The ambient temperatures and wind speeds used were similar to those commonly expected on the Canadian prairies. Environment Canada (1992) provided yearly averages of 2.4☜C and 18 km/h for the Winnipeg area. Wind speeds of 5-35 km/h with increments of 10 km/h were used in the models. These values were selected to provide a distinct indication of the effects of wind. Internal-external temperature differences ranging from 0.0-50.0☜C were used to study the effects of temperature.

Standardized coefficients for terrain and shielding (Sherman and Grimsrud, 1980) were selected to adjust the wind speed and the temperature effect. Most grain storage sites in Canada are located on farms in rural areas. Terrain parameters of ✂ = 0.85 and ☎ = 0.20 are recommended for this class of terrain (Class III, Sherman and Grimsrud, 1980). The recommended shielding coefficient for a structure located within two building heights of some obstructions is

C´ = 0.285 (Sherman and Grimsrud, 1980).

For the LBL model, the rate of gas loss is determined by the power law equation (Eq. 1):

$$Q = b(➂ P)^n \qquad (1)$$

where: Q = ventilation (gas loss) rate (m^3/s),

➂P = internal-external pressure drop across building envelope (Pa)

b = flow coefficient, (dimensionless), and

n = flow coefficient (dimensionless).

Flow through the leaks was assumed to be turbulent, therefore, the exponent, n, of this equation was set to 0.50 (Banks and Annis, 1984).

The value of b must be determined for each line, and is given by (White, 1986):

$$b = A_o\sqrt{\frac{2}{\tilde{n}}} \qquad (2)$$

where: A_o = effective leakage area (m^2), and □ = gas density inside (kg/m^3).

The effective leakage area (ELA) for each bin must be estimated experimentally.

The flow coefficients for the BA model were similar to those of the LBL model with the exception that the b coefficient included the orifice discharge coefficient (C_d). The discharge coefficient is a function of the Reynolds number (Rouse, 1946).

The flow through a building envelope is dominated by turbulent flow. Therefore, a discharge coefficient of 0.61 was used for the turbulent flow regime (Rouse, 1946).

EXPERIMENTAL PROCEDURES

Effective leakage area tests

The ELA of the test bin was measured by conducting fan pressurization tests according to the ASTM Standard practice of determining the air leakage rate through a building envelope (Anon. 1993). A schematic diagram of the apparatus is illustrated in Fig. 1. The procedure consisted of: 1) pressurization of the bin by forcing a measured airflow through the bin; and 2) measurement of the static pressure drop (P_{int} - P_{ext}) that was created across the building envelope. Several flow rates and corresponding pressure drops were measured. The data were used to determine the experimental flow coefficients *n* and *b* by conducting a two-parameter fit to the power law function (Eq. 1) using procedure GLM of SAS (SAS 1982). The ASTM Standard (Anon. 1993) recommends a depressurization test in addition to the pressurization test. Due to the limitations of the equipment, the depressurization tests were not conducted.

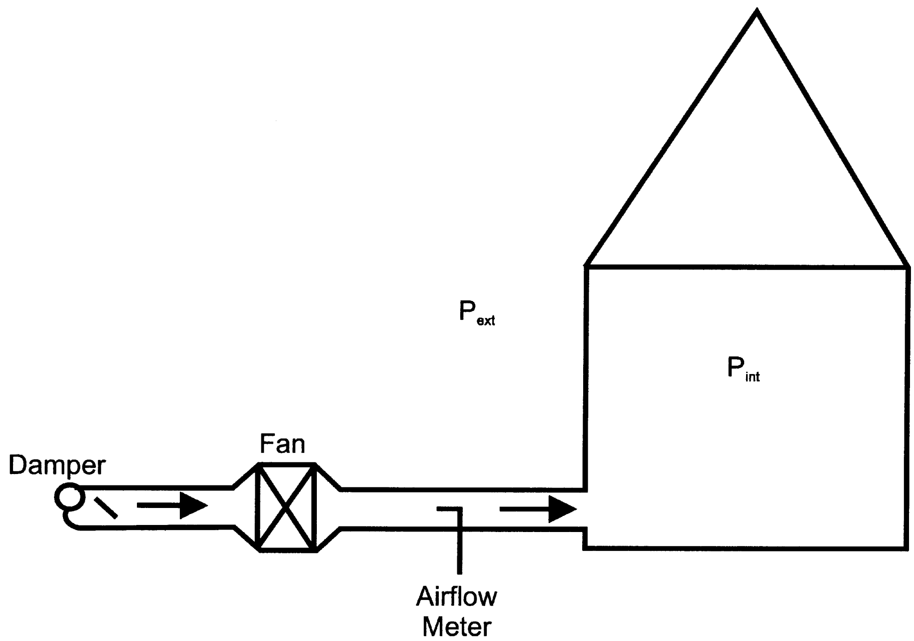

Fig. 1. Schematic diagram of the fan pressurization equipment.

Once the flow coefficients were known, Eq. 1 was used with a reference pressure of 4 Pa to determine the ventilation rate, Q_{4Pa}. The effective leakage area of the bin was then found by using this rate (Q_{4Pa}) and the reference pressure ($4Pa$) in Eq. 3 and solving for A_o. This leakage area represented the total effective leakage area in the bin envelope including cracks and holes.

$$Q = A_o \sqrt{\frac{2}{\rho} \Delta p} \qquad (3)$$

The estimated ELA was validated by mounting a thin flat plate, that contained an orifice hole into an opening of the building envelope. The plate must be less than 1.60 mm thick and the orifice hole must have a known diameter with a tolerance of $\pm$ 0.80 mm (Anonymous, 1985). The effective orifice area ($A_{o.orifice}$) is the physical area of the orifice hole multiplied by the orifice coefficient, $C_d = 0.61$. The value of $A_{o.orifice}$ must be greater than A_o of the structure being tested. This ensures that measurement errors do not dominate the ELA estimate. The effective leakage area of the structure when the orifice hole was mounted in the building envelope, A'_o, was determined using the fan pressurization method. The following equation was then used to determine the experimental effective leakage area of the orifice hole.

$$A_{orifice} = A'_o - A_o \qquad (4)$$

This value was compared to $A_{o.orifice}$ for validation. The acceptable percent error between the experimentally measured $A_{orifice}$ and the effective orifice area $A_{o.orifice}$ is $\pm$ 25% (Anon. 1985).

Details for the bin

The bin (Fig. 2) was constructed of corrugated panels of galvanized steel that were bolted together. Most seams contained a rubber gasket and silicone to improve the seal; however, holes and cracks were visible in the bin wall and roof. The bin had a concrete floor and was equipped with a 0.46 m diameter $\times$ 4.7 m long circular duct resting on the floor. This duct had perforations for a length of 3.3 m beginning from the far end of the duct. The bin was empty for the fan pressurization tests.

A circular duct (0.75 m diameter $\times$ 7 m long) outside the bin was connected to the inlet of a sealed 3.73-kW axial fan. A flow straightener (0.48 m diameter $\times$ 1 m long) was later added to the inlet of the duct to reduce fluctuations in the manometer readings. A pitot tube was used to measure the airflow rate and was located 6 m downstream of the duct inlet and 1 m upstream of the fan. The velocity pressure was measured with a manometer at eight sampling locations and was converted to velocity (m/s) and averaged by dividing by the number of sampling points. The flow rate was determined using the area of the duct and the calculated average velocity. Four different induced envelope pressure drops and corresponding airflow rates were measured. The air blockage plates for these tests had openings of 305, 406, 483, and 508 mm diameter.

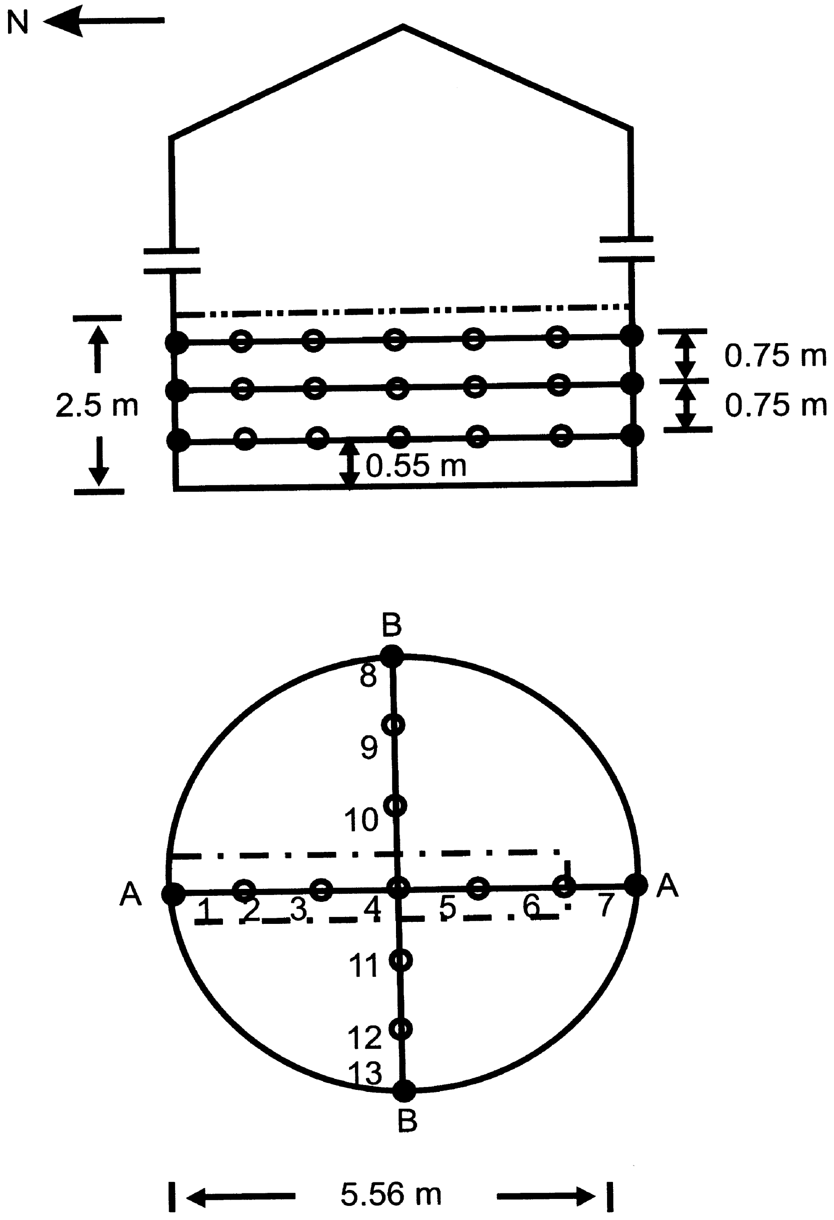

Fig. 2. Schematic diagram of the full-size bin, 5.56 m in diameter with a circular duct on the floor (gas sampling points are represented by "⊖" and pressure measurement points are represented by "●").

Semi-rigid nylon tubes (3.2 mm outside diameter, 50 mm long) located at three different heights (0.55, 1.30, and 2.05 m above the floor) and four equi-spaced radial positions in the bin wall were used to measure the envelope pressure drop. The manometer inlet was connected to the tubes and the induced pressure drops across the bin wall were measured. For each flow rate, the average envelope pressure drop was determined.

A second pressurization test of the empty bin was conducted which included a polyvinyldichloride (PVDC) sheet taped to the wall of the full-size bin at a height of 2.5 m above the floor. This was done in accordance with the CO_2 experiments conducted by Alagusundaram (1993) which used a PVDC sheet on the top surface of a stored wheat bulk in the same bin. The PVDC sheet eliminates the leakage at the roof during the fan pressurization tests. The resulting ELA was for 2.5 m of the bin wall and any leakage area through the floor.

Experimental gas loss tests

Carbon dioxide concentration levels in the same full-size bin, half filled with wheat and covered with a PVDC sheet, were previously measured by Alagusundaram (1993). Therefore, it was not necessary to repeat these tests as the data were available for comparison with the mathematical models.

RESULTS AND DISCUSSION

Effective leakage area

To conform to the pressure drop requirements of the ASTM Standard (Anonymous, 1993), only three data points were obtained during the fan pressurization tests. The ELA of the full-size bin was estimated to be 746 cm^2. Considering that the wall to roof joint of the bin contained several large gaps and that the roof contained an open-air vent, the estimated ELA was reasonable. Because experimental data for CO_2 loss were for a 2.5 m high portion of the bin, fan pressurization tests with PVDC sheet attached to the wall at 2.5 m were conducted. These tests failed because the PVDC sheet peeled off during pressurization. Therefore, an alternative method was used to estimate the ELA.

The ELA of a structure can be determined by physically measuring the leakage area and then multipling the value by a discharge coefficient of 0.61. For this procedure, a feeler gauge was used to measure the width of any gaps that were present between the seam of two bolted panels. All of the horizontal seams were completely covered with silicone sealant and the feeler gauge could not be used. These seams were assumed to be perfectly sealed. Of the 26 vertical seams, all but 5 were completely covered with silicone sealant. These seams were also considered to be perfectly sealed. Using the feeler gauge on the five unsealed vertical seams, it was found that the panels contained approximately the same number of gaps with similar openings. For each seam there were 12 gaps that were 25 mm long, 0.813

mm wide and 12 gaps that were 25 mm long, 0.012 mm wide. The total physical leakage area for the five seams was calculated to be 12.6 cm^2. Multiplying this value by an orifice coefficient of 0.61 gave an effective leakage area of 7.7 cm^2.

Experimental gas loss tests

The experimental tests of CO_2 gas loss were conducted previously by Alagusundaram (1993) (Table 1). For these tests, the bin contained wheat which filled the bin 2.5 m above the floor. The driving forces for the loss of gas were the wind, temperature, and chimney effect. To prevent CA gases from escaping to the headspace of the bin, the top surface of the grain was covered and sealed with a PVDC sheet. Carbon dioxide gas was introduced as dry ice in the air duct and samples were taken and analyzed using a gas chromatograph (Model: Sigma 3B, Perkin Elmer). The average wind speeds and ambient temperatures, which were measured at the Winnipeg International Airport were obtained from Environment Canada (Anon. 1992) Weather Service. The gas loss rate for each experiment was calculated using Eq. 5. A summary of these data is presented in Table 1.

TABLE 1
Wind, temperature, CO_2 gas levels, and gas loss rates for experimental tests using the full-size bin (Alagusundaram, 1993)

Test #	Avg. wind speed (km/h)	Avg. ambient temp (°C)	Avg. grain temp (°C)	c_i (%)	c_f (%)	Δt (h)	$Q \times 10^{+6}$ (m^3/s)
1	10.9	14.9	14.5	22.3	10.2	15	54.3
2	3.2	15.4	14.5	25.4	6.6	18	70.7
3	8.3	16.4	16.0	21.9	7.0	16	62.6
4	18.3	17.0	16.0	52.6	34.2	15	82.8
5	16.9	16.9	16.0	56.9	26.3	15	137.7
6	5.3	16.2	17.4	48.4	39.0	9	70.4
7	8.2	17.0	17.4	49.5	39.8	16	41.1
8	11.1	17.8	15.2	32.4	21.2	15	50.2
9	12.9	19.4	15.2	43.1	22.3	15	93.2

LBL model

There appears to be no direct correlation between the wind speed and experimental gas loss rate. According to the LBL model, however, the rate of gas loss from this bin (A_o = 7.7 cm^2, ✂ = 0.85, and ☎ = 0.20) ranges from 130 × 10^{-6} m^3/s at a wind speed of 5 km/h to 890 × 10^{-6} m^3/s at a wind speed of 35 km/h.

When filled with wheat to a height of 2.5 m and assuming a porosity of 40%, a pore volume of 24.3 m^3 is present in the bin. Taking the average gas loss rate (74×10^{-6} m^3/s) and dividing by the pore volume gives an air change rate of 0.26 per day.

The chimney effect was predicted using the LBL model for hypothetical temperature differences. A small temperature gradient of 10°C is significant enough to cause a rate of gas loss comparable to a 10 km/h wind in a structure that contains an ELA of 7.7 cm^2. The predicted gas loss increases to 560×10^{-6} m^3/s when the temperature difference between the inside and outside air is set equal to 50°C.

BA model

The BA model overpredicted gas loss rates considerably for the full-size bin and thus cannot be used for optimizing CA treatments without further development.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. The experimental air change rate from the bin was 0.26 volumes per day.
2. Fan pressurization tests can be used to determine the effective leakage area of a rigid structure. The portion tested must be separated from the non-vertical part of the bin by flexible PVDC sheet. Bolting the sheet around the circumference may create enough rigidity to facilitate ELA determination.
3. The LBL model over-predicted the rates of gas loss by an average of 5.8 times the experimental rate.
4. A high level of accuracy of the predicted rates of CO_2 gas loss cannot be expected until clearer experimental relationships are developed between gas loss and: a) wind, b) temperature differences, and c) gas density differences.

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