Journal of Stored Products Research 64 (2015) 13–20

Contents lists available at ScienceDirect

Journal of Stored Products Research

journal homepage: www.elsevier.com/locate/jspr

Evaluation of the superposition method for predicting gas leakage rates during fumigations in empty model silos

Watcharapol Chayaprasert [a,*], Kanlaya Nukham [a], Anak Sukcharoen [b]

[a] Department of Agricultural Engineering, Kasetsart University, Kamphaengsaen Campus, 1, Hmu 6, Malaiman Road, Kamphaengsaen, Nakhon Pathom, 73140, Thailand

[b] National Agricultural Machinery Center, Kasetsart University, Kamphaengsaen Campus, 1, Hmu 6, Malaiman Road, Kamphaengsaen, Nakhon Pathom, 73140, Thailand

ARTICLE INFO

Article history:
Received 22 May 2015
Received in revised form 30 July 2015
Accepted 30 July 2015
Available online 14 August 2015

Keywords:
Fumigation
Pressurization test
Superposition method
Half-loss time

ABSTRACT

In precision fumigation practices, half-loss time (HLT) is used for forecasting the success of a fumigation job. The objective of this study was to explore the feasibility of using the superposition method for predicting HLTs. The superposition equation describes the total gas leakage rate from a structure in terms of prevailing wind speeds, temperature differences between inside and outside of the structure, and the effective leakage area (ELA) of the structure. Two fumigation experiments were conducted in 228.5 and 2160 l cylindrical polypropylene model silos using carbon dioxide as a tracer gas. The pressure-flow rate pressurization test was performed before each fumigation in order to determine the ELA of the silo. The resulting fumigant concentration curves followed first-order kinetic characteristics. The purpose of the first experiment was to determine the wind and stack coefficients of the silos. In order to evaluate the accuracy of the superposition method, in the second experiment three replicates of fumigation trials were conducted for each model silo at combinations of three constant wind speeds and four constant temperature differences. The recorded concentration decay curve of each fumigation trial was fitted with the first-order kinetic equation to determine the actual HLT. The actual HLTs of the small and large silos ranged from 3.21 ± 0.47 to 6.71 ± 0.62 h and from 4.49 ± 0.67 to 18.74 ± 0.24 h, respectively. Then, these actual HLTs were compared with the HLTs predicted by the superposition equation. The previously determined coefficients were incorporated in the prediction of HLTs. The percentage prediction errors ranged from 1.65 ± 0.50 to 15.70 ± 1.10% for the small silo and from 1.76 ± 1.21 to 10.43 ± 1.36% for the larger one. The actual and predicted HLTs were linearly correlated with slopes close to unity ($R^2 > 0.894$). The results of this research illustrated that fumigant concentration decay rates can be satisfactorily predicted by the superposition method.

1. Introduction

The efficacy of a fumigation job depends on the fumigant concentration and exposure time. To ensure successful fumigation, these two influencing factors must exceed certain required thresholds. However, often times continuously maintaining high levels of fumigant concentrations is not feasible due to leaky structures and the operator's schedule does not allow for long exposure time. Gas leakage rate during fumigation is quantified as the time by which the fumigant concentration reduces by half, namely the half-loss time (HLT). In the current precision fumigation practices, the fumigation process is optimized by estimating the fumigant leakage rate (i.e., HLT) in advance so that a proper amount of the fumigant (i.e., dose) is precisely calculated and released. HLT is typically estimated using historical fumigant concentration records. However, it is commonly known that HLT is influenced by weather conditions and sealing quality. Using computational fluid dynamics (CFD) simulations, Chayaprasert et al. (2009) demonstrated that variations in surrounding wind and ambient temperature conditions (i.e., wind and stack effects) could cause the HLTs of 10 annual fumigations in a flour mill to vary from 10 to 26 h. A computer simulation fumigation study by Cryer (2008) which considered only the surrounding wind factor indicated a similar finding. Chayaprasert et al. (2012) conducted three methyl bromide and three sulfuryl fluoride fumigations in a 9628 m^3 pilot flour mill

* Corresponding author.
E-mail address: fengwpc@ku.ac.th (W. Chayaprasert).

http://dx.doi.org/10.1016/j.jspr.2015.07.007
0022-474X/

and found that fumigant leakage rates were predominantly a function of surrounding wind speed. Two primary types of pressurization tests are the pressure decay (P-t) test and the pressure-flow rate (P-Q) test (Banks et al., 1974; Navarro, 1999). In the P-t test, also known as the variable pressure test, air is pushed into an enclosure. Once a prespecified gauge pressure is reached, the air supply is stopped and the pressure decreases due to leakage. The time for the pressure to decay from an initial level to its half indicates air-tightness of the enclosure. The standardized P-Q test, also known as the blower door test, is usually used for quantification of air-tightness of buildings (ASTM, 1996). In addition to weather conditions, Chayaprasert and Maier (2010) used a combination of empirical P-Q tests and CFD simulations to demonstrate that sealing quality also affects fumigant leakage rates. Chayaprasert et al. (2010) validated the CFD modelling approach of Chayaprasert and Maier (2010) using the data from two fumigation trials presented in the study of Chayaprasert et al. (2012). To calculate air infiltration rates into residential structures, the heating, ventilation, and air conditioning (HVAC) industry typically uses the standardized pressurization test and the superposition method which take into account the weather and air-tightness factors (ASHRAE, 2001). Lawrence et al. (2012) performed P-Q tests before six fumigation trials in five commercial flour mills and compared the air-tightness among the mills by using the P-Q test results to calculate the effective leakage area (ELA) of each mill. In the next section of this article, the relationship between the infiltration rate and HLT, and how the pressurization test and superposition method could be applied for predicting the HLT are described. Chayaprasert et al. (2008a) evaluated the HLT prediction accuracy of the superposition method against the validated CFD model developed by Chayaprasert et al. (2008b). This group of researchers simulated 11 annual fumigation jobs in a 28,317 m^3 flour mill using the CFD model and hourly average historical weather data of the assumed fumigation exposure periods between 1996 and 2006. They found that the HLTs predicted by the superposition method were mostly ±20% different from those given by the CFD model. However, no actual fumigation experiments were conducted in their study.

Based on findings of the previously mentioned studies, accurate estimation of HLTs in actual fumigation by the superposition method is promising. As a result, the objective of the present study was to further evaluate the feasibility of using the superposition equation in combination with the pressurization test as a tool for predicting HLTs by conducting fumigation experiments in two physical model silos.

2. Materials and methods

2.1. Theoretical calculations

Banks and Annis (1984), Cryer and Barnekow (2006) and Chayaprasert (2007) described the characteristics of fumigant concentration decay during a fumigation job as a first-order kinetic approximation:

$$\frac{C_t}{C_i} = \frac{1}{2^{\frac{t}{HLT}}} \tag{1}$$

where C_t is the fumigant concentration (g/m^3) at the elapsed exposure time, t (h), and C_i is the initial concentration (g/m^3) (i.e., t = 0 h). The HLT (h) dictates the rate at which the fumigant concentration decreases. The concentration decrease is caused by volumetric exchange between the fumigant-air mixture inside and the fresh air outside the fumigated structure. It has been shown elsewhere that the HLT is inversely proportional to the total volumetric leakage rate (i.e., infiltration rate), Q (m^3/s) (Banks et al., 1983; Banks and Annis, 1984; Chayaprasert, 2007):

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

where V is the volume of the fumigated structure (m^3). In the superposition method, the leakage rates due to wind and stack effects, Q_w and Q_s (m^3/s), respectively, are estimated separately and the total volumetric leakage rate is calculated as the square root of the sum of the squares of the two (ASHRAE, 2001):

$$Q = \sqrt{Q_s^2 + Q_w^2} = \frac{A_L}{1000}\sqrt{C_s \Delta T + C_w U^2} \tag{3}$$

where C_s is the stack coefficient ($(l/s)^2/cm^4$-K), C_w is the wind coefficient ($(l/s)^2/cm^4$-$(m/s)^2$), ΔT is the average temperature difference (K) between the inside and outside of the structure, and U is the average wind speed (m/s) surrounding the structure. Note that the stack and wind coefficients are primarily characterized by the shape of the structure, the locations of the leakage openings, and the wind direction. The ELA, A_L (cm^2), which is an indication of the structure's air-tightness (i.e., sealing quality), is calculated as (ASHRAE, 2001):

$$A_L = \frac{10,000b}{C_D}\sqrt{\frac{\rho}{2}}\Delta p_r^{(n-0.5)} \tag{4}$$

where ρ is the air density (kg/m^3), C_D is the dimensionless discharge coefficient, and Δp_r is the reference pressure difference (Pa). Note that C_D and Δp_r are constants and their values are suggested to be 1 and 4 Pa, respectively, by Sherman and Grimsrud (1980). The flow coefficient, b (m^3/s-Pa^n), and the pressure exponent, n (dimensionless), are obtained by conducting the P-Q pressurization test on the structure. In a P-Q test, the pressure difference between the inside of the tested structure and the natural barometric pressure, Δp (Pa), is incrementally increased using a variable-speed fan(s). The fan operates at different constant speeds and at each fan speed the pressure difference and the air flow rate through the fan, q (m^3/s), is recorded. The flow coefficient and pressure exponent are determined from the relationship between the pressure difference and the air flow rate:

$$q = b(\Delta p)^n \tag{5}$$

Note that the upper and lower limits for the pressure exponent are 0.5 for fully developed turbulent flow and 1 for laminar flow, respectively (Walker et al., 1998). If the weather conditions, the stack and wind coefficients, and the volume and ELA of the structure are known in advance, the HLT of a fumigation job can be predicted by substituting Eq. (3) into Eq. (2):

$$HLT = \frac{V}{\frac{A_L}{1000}\sqrt{C_s \Delta T + C_w U^2}}\frac{\ln(2)}{3,600} \tag{6}$$

Assuming zero temperature difference, Eq. (6) can be re-arranged as:

$$C_w = \frac{1}{U^2}\left(\frac{1000}{A_L}\frac{V}{HLT}\frac{\ln(2)}{3,600}\right)^2 \tag{7}$$

Similarly, assuming zero wind speed it can be re-written as:

$$C_s = \frac{1}{\Delta T}\left(\frac{1000}{A_L}\frac{V}{HLT}\frac{\ln(2)}{3,600}\right)^2 \tag{8}$$