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Evaluating Importance and Implementation of the Building Pressurization Test in Structural Fumigation Using Computer Simulations

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Abstract: Pressurization In a previous study, a validated Computational Fluid Dynamics (CFD) model of the structural fumigation process in a flour mill was utilized to evaluate the effect of multi – year weather conditions (1996 – 2006) on the half – loss time (HLT) and concentration × time (Ct) product, concluding that past fumigation data should not be the primary means for quantifying the effectiveness of temporary structural sealing. In the present study, using the same CFD model the standardized building pressurization test and superposition method commonly used for heating/cooling load and in-door air quality calculations in buildings were evaluated for prediction of HLT and Ct product. A simulated test was performed in order to determine the flour mill's effective leakage area. Then, the simulated mill was subjected to several fixed environmental conditions to determine the stack and wind coefficients which were necessary for the superposition calculation. The HLTs and Ct products generated by the 11 – year fumigation simulations were compared with the corresponding values predicted based on the superposition method. The HLT and Ct product predictions were within ±20 and ±10% of the simulated values, respectively, except for one simulated fumigation. These results showed that the pressurization test and superposition method have potential application benefits for optimizing the structural fumigation process.

Key words: structural fumigation, half – loss time, computational fluid dynamics (CFD), building pressurization

Introduction

Optimizing fumigant usage for a structural fumigation requires that the fumigant leakage rate (i. e., half-loss time, HLT) be predicted so that the target concentration × time product (i. e., Ct product) is precisely reached at the end of the exposure period. HLT is influenced by weather conditions, especially wind and ambient temperature. However, since the HLT concept was introduced, the relationship between HLT and weather conditions has never been quantified. While fumigators typically rely on concentration data recorded from past fumigations to determine the HLT of a structure, a simulation study of fumigation in a flour mill[1] found that the HLT between fumigations could vary up to 100% due to the variation in weather conditions. In addition to weather conditions, the HLT is also affected by the air-tightness of the structure, which can vary due to aging and changes in sealing quality. As a result, the prediction of HLT based solely upon past fumigation data is subject to substantial uncertainty.

The standardized pressurization test[2], also known as the blower door test, and the superposition of the wind and stack effects have been used by the heating, ventilation, and air conditioning (HVAC) industry to quantify air infiltration into structures for energy saving and indoor air quality purposes[3]. This superposition was primarily developed for residential houses. However, the use of the pressurization test in commercial/industrial structures is not uncommon. Fumigant leakage is linked to the infiltration process. Thus, the pressurization test and superposition method could be applied for the prediction of HLT and Ct product in structural fumigation. The objective of this study was to utilize the validated Computational Fluid Dynamics (CFD) model developed by Chayaprasert et al. [4] to evaluate the pressurization test and superposition method for prediction of structural fumigation performance.

Materials and Method

Theoretical Calculations

One of the correlations that is most widely used to describe the relationship between the

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infiltration rate, Q (m^3/s), and the pressure difference across the building envelope, (p (Pa), is the power law equation:

$$Q = c(\Delta p) \qquad \text{Eq. 1}$$

where c is the flow coefficient ($m^3/s\ Pa^n$). The pressure exponent, n is dimensionless and has the limiting values of 0.5 and 1 for fully developed turbulent and laminar flow, respectively[5]. The characteristic constants, c and n, are different for different buildings. To conduct the pressurization test, one or more specifically calibrated fan(s) installed at the perimeter of the structure are used to induce a pressure difference across the building envelope. The airflow rate that is required to maintain this induced pressure difference is recorded. By testing at multiple pressure levels, the power law relationship of the building can be established. Natural infiltration is a non-linear and complex process. Most infiltration models rely on a simplification method called superposition in which the wind and stack effects are determined separately and then combined together based on a predefined correlation. One additive correlation is[3]:

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

where C_s is the stack coefficient ($(L/s)^2/cm^4 - K$), C_w is the wind coefficient ($(L/s)^2/cm^4 - (m/s)^2$), (t is the average indoor − outdoor temperature difference (K), and U is the average local wind speed (m/s) typically measured at a nearby weather station. The effective leakage area, A_L (cm^2), is calculated as:

$$A_L = 1000\ Q_r\sqrt{\frac{\rho/2\Delta p_r}{C_D}} \qquad \text{Eq. 3}$$

where ρ is the air density (kg/m^3), C_D is the dimensionless discharge coefficient, and Q_r is the infiltration rate (m^3/s) predicted at the reference pressure difference, Δp_r (Pa). Eq. 3 implies that all cracks and openings in the building are collectively represented as one equivalent leakage area and a corresponding discharge coefficient. Substituting Eq. 1 into Eq. 3 yields:

$$A_L = \frac{10000\ c}{C_D}\sqrt{\frac{\rho}{2}}\Delta p_r^{(n-0.5)} \qquad \text{Eq. 4}$$

While the flow coefficient, c, and the pressure exponent, n, can be determined from the pressurization test data, the reference pressure difference, Δp_r, and the discharge coefficient, C_D, are typically chosen by the user. Sherman and Grimrud[6] used $\Delta p_r = 4$ Pa and $C_D = 1$.

Simulation Setups

The CFD model used in this study was constructed based on a 28,317 m^3 flour mill and was described in detail by Chayaprasert et al. [4]. The pressurization test was simulated by performing eight steady − state flow simulations in which pressure differences of ±2.5, ±10, ±20 and ±50 Pa between the inside and outside of the mill were investigated. Note that both the positive and negative pressure ranges were included, representing both pressurization and de − pressurization (suction). The primary result obtained from the simulated pressurization test was the volume air flow rate through the leakage areas on the mill envelope for each simulation. By fitting this result with Eq. 1, the c and n constants were determined. Assuming $\Delta p_r = 4$ Pa and $C_D = 1$, the effective leakage area, A_L, (Eq. 4) was then calculated.

Assuming zero wind speed, Eq. 2 can be re − written as:

$$Q = \frac{A_L}{1000}\sqrt{C_s\Delta t} \qquad \text{Eq. 5}$$

Similarly, assuming zero temperature difference Eq. 2 can be re − written as:

$$Q = \frac{A_L}{1000}\sqrt{C_w U^2} \qquad \text{Eq. 6}$$

Once the correlated data points of Q and (t are obtained, C_s can be calculated by fitting these data points with Eq. 5. A similar approach can be applied to Eq. 6 for calculating C_w. The data points that were fitted with Eq. 5 were obtained from 16 simulations. Two indoor temperatures were selected, 25 and 30 ℃. At each indoor temperature, eight outdoor temperatures that yielded temperature differences of ±5, ±10, ±15 and ±20 ℃ were selected. Another simulation set was performed to acquire the Q − vs − U correlation in Eq. 6. The C_w value of a structure is unique for every wind direction, depending on the layout of surrounding area. It has been shown that wind direction has a considerable effect on the fumigant leakage rate[1,4]. However, it was not possible to determine a C_w value for every possible wind direction. In order to minimize the number of simulations, only the wind coefficients corresponding to eight wind directions (i. e., N, NE, E, SE, S, SW, W and NW) were determined. Four simulations each with different fixed wind velocities (i. e., 4, 8, 12 and 16 m/s) were performed for each wind direction.

Data Processing

Chayaprasert et al. [1] utilized the CFD model to evaluate the effect of multi-year weather conditions on the HLT and Ct product. Eleven sulfuryl fluoride (SF) fumigation simulations were performed using hourly average historical weather data of the same time period between 1996 and 2006. It was assumed that for each year's simulation (1996, 2006) the fumigation started at 12:00pm on 4 July and lasted 24 hours. The HLT of each simulation was determined by first normalizing the average fumigant concentration curve by the initial concentration. Next, the normalized concentration curve was fitted with the following equation:

$$C_{norm} = \frac{1}{2^{\frac{t}{HLT_{sim}}}} \qquad \text{Eq. 7}$$

where C_{norm} is the normalized concentration (dimensionless) and t is the elapsed time (hr). The Ct product was effectively the area under the average concentration curve, which was calculated by integrating the non-normalized concentration curve.

In the present study, the HLT and Ct product determined from the average fumigant concentration curve were compared with the respective values predicted using the superposition method. The HLT prediction was calculated using the following equation:

$$HLT_{sup} = \frac{V}{Q}\frac{\ln(2)}{3600} \qquad \text{Eq. 8}$$

where V is the volume of the structure (m^3) and Q is the volumetric gas leakage rate (m^3/s) predicted by the superposition method. For each of the 11 – year fumigations, the gas leakage rate, Q, was calculated by substituting the average ambient temperature and wind speed into Eq. 2 and selecting the wind coefficient based on the most dominant wind direction. The V/Q term is the reciprocal of the air change rate. A different form of Eq. 8 is used by the tracer gas dilution standard test method[7] to describe the relationship between the tracer gas concentration decay and air change rate in a single volume. The Ct product was predicted as follows:

$$Ct_{sup} = \frac{-C_{i,sim}HLT_{sup}\left(2^{-\frac{t}{HLT_{sup}}} - 1\right)}{\ln(2)} \qquad \text{Eq. 9}$$

where $C_{i,sim}$ is the initial gas concentration (g/m^3) determined from the simulation. This equation is essentially the integration of the non – normalized form of Eq. 7.

Results and Discussion

By fitting the data points of the simulated pressurization test with Eq. 1, the flow coefficient, c, and the pressure exponent, n, were determined to be 0.293 and 0.5, respectively. The discharge coefficient, C_D, and air density were assumed equal to 1 and 1.18, respectively. Substituting these c, n, C_D and (values in Eq. 4 resulted in an effective leakage area, A_L, of:

$$A_L = \frac{10000 \times 0.293}{1}\sqrt{\frac{1.18}{2}}\,\Delta p_r^{(0.5-0.5)} = 2251$$
$$cm^2$$

The resulting infiltration rates of the simulations performed for determining the stack coefficient yielded the following correlation between the temperature difference, (t, and the infiltration rate, Q:

$$Q = 0.0673 \times \Delta t^{0.5}$$

The stack coefficient was calculated by equating the above equation to Eq. 5:

$$\frac{A_L}{1000}\sqrt{C_s \Delta t} = 0.0673 \times \Delta t^{0.5}$$
$$\frac{2251}{1000}\sqrt{C_s} = 0.0673$$
$$C_s = 0.000894$$

The resulting infiltration rates of the simulations performed for determining the wind coefficients yielded the following linear correlation between the infiltration rate, Q, and wind velocity, U:

$$Q = au$$

where the slope a varied between 0.0125 0.0664 for different wind directions. The wind coefficient was calculated by equating the above equation to Eq. 6:

$$\frac{A_L}{1000}\sqrt{C_w U^2} = aU$$
$$\frac{2251}{1000}\sqrt{C_w} = a$$
$$C_w = 2.251 \times a$$

The resulting wind coefficients for all wind directions were between $0.308 \times 10^{-4} \times - 8.697 \times 10^{-4}$. As previously mentioned, this characteristic difference was a result of the fact that the surrounding landscape around the flour mill is not the same in all directions. Grain bins and silos are located on the north end of the flour mill. These structures reduced the dynamic head of the wind from the north and north-west directions. The south side of the mill is not exposed to the external environment, but attached to a grain bulk structure and a packaging building. Therefore, the wind coefficients of the mill for the north, north-west and south wind directions were noticeably lower than those for the other wind directions.

The historical weather data and fumigation results of the 11-year fumigation simulations[1] as well as the respective HLT and Ct product predictions by the superposition method are summarized in Table 1. Wind speed and ambient temperature are given in terms of average values and standard deviations. The average wind speeds and outdoor temperatures were between 1.5 and 5.1 m/s and 16.2 and 29.1℃, respectively. Wind direction is given in terms of the most dominant wind direction (i. e., the mode) and the numbers of hours during which the mode wind direction occurred. A greater number of hours of a particular mode wind direction indicated that the wind was relatively steady in terms of traveling direction. The initial concentrations were between 44.6 and 54.3 g/m^3. The simulated HLTs and Ct products ranged from 10.7 to 23.3 hours and from 476 to 840 $g \cdot h/m^3$, respectively. Note that the superposition method assumed fixed weather conditions in predicting the HLT and Ct product while those used in the simulations did not remain constant during the fumigation period (i. e., outdoor temperature varied in a sinusoidal fashion, and both wind speed and direction randomly varied). The HLT and Ct product predictions were however relatively accurate. For all except one simulation (2005), the HLT and Ct product difference percentages were within (20 and 10%), respectively.

Table 1. The weather conditions and results of the 11 - year fumigation simulations as well as the respective HLT and Ct product predictions by the superposition method.

Year	Outdoor Temp. ^{a} (℃)	Wind Spd. ^{a} (m/s)	Wind Dir. ^{a} (degree)	Simulation^a			Superposition		% Difference	
	Avg. [S. D.]	Avg. [S. D.]	Mode [# of hrs]	Init. Conc. (g/m^3)	HLT (hr)	Ct ($g \cdot h/m^3$)	HLT (hr)	Ct ($g \cdot h/m^3$)	HLT	Ct
1996	20.9 [4.4]	1.5 [1.3]	0 [21]	54.3	23.3	840	19.2	773	18	8
1997	16.2 [3.5]	4 [1.6]	315 [16]	49.7	13.6	633	13.6	624	0	1
1998	23.3 [2.9]	4.4 [1.3]	0 [11]	53.4	18.2	757	18.9	757	-4	0
1999	28.3 [3.6]	4 [1.6]	225 [20]	49.6	13.2	598	14.6	641	-11	-7
2000	24.4 [2.5]	2.1 [1.9]	0 [10]	52.8	19.6	752	23.5	798	-20	-6
2001	22.5 [3.5]	3.5 [0.9]	270 [14]	52.5	15.5	696	13.4	654	14	6
2002	29.1 [3.3]	3.2 [0.8]	45 [8]	51.2	19.8	730	22.4	763	-13	-5
2003	25.2 [4.9]	5.1 [2.6]	225 [7]	48.5	12.5	571	11	552	12	3
2004	23.6 [3.7]	4.7 [2.4]	270 [14]	44.6	10.7	476	11.2	511	-4	-7
2005	25.5 [4.1]	4.1 [1.3]	0 [6]	49.7	15.9	658	22.1	738	-39	-12
2006	22.4 [3.1]	4.8 [1.4]	45 [10]	49.7	15.7	672	12.8	607	18	10

aData generated by Chayaprasert et al. [1]

Overall, the simulated pressurization test and superposition method yielded satisfactorily accurate predictions of HLT, suggesting their benefits to optimizing structural fumigation.

Nevertheless, due to the fact that this study was simulation – based, several simplifications were assumed. While it was utilized on a flour mill structure in this study, the superposition method was originally developed for application in residential houses. All results in this study were generated based on a CFD model which already includes a set of inherent assumptions such as pressure distribution on the external walls, leakage characteristic, and numerical rounding. Accuracy of the effective leakage area, A_L, can be affected by the choice of the discharge coefficient, C_D, which can be between 0.6 and 1 depending on the pressurization test standard. It is not possible to obtain the true values of the stack and wind coefficients, C_s and C_w. Thus, the accuracy of the superposition method will always be compromised by the estimation of their values. The accuracy of the Ct product prediction is affected not only by the HLT, but also the initial concentration. Unlike in this study, in practice the initial concentration has to be estimated by dividing the amount of initially released fumigant by the estimated structure volume before the fumigation starts. As can be seen in Eq. 9, the Ct product is directly proportional to the initial concentration. In other words, the error percentage in the initial concentration estimation yields the same error percentage in the Ct product prediction (e. g., 10% error in the structure volume estimation would result in 10% error in the Ct product prediction). As a result, the pressurization test and superposition method should be further evaluated experimentally. In addition, the costs versus benefits of the pressurization test should also be properly analyzed.

Conclusions

The application of the pressurization test and superposition method for prediction of structural fumigation performance were evaluated by CFD simulations with the CFD model developed by Chayaprasert et al. [4] A simulated pressurization test was performed to determine the structure's effective leakage area. Then, the simulated structure was subjected to several fixed environmental conditions to determine the stack and wind coefficients. Finally, the HLTs and Ct products generated by the 11 – year fumigation simulations[1] were compared with the values estimated based on the superposition method. The results showed that the pressurization test and superposition method have potential application benefits for optimizing the structural fumigation process. The HLT and Ct product predictions were within (20 and (10% of the simulated values, respectively, in 10 out of 11 years. However, additional experimental investigation is needed to verify their application in practice.

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