# Prediction of half-loss times of fumigations in a model silo by the superposition method

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## Abstract

In precision fumigation practices, half-loss time (HLT) is used for determining the amount of fumigant needed and forecasting the success of a fumigation. Fumigators have been relying on historical gas concentration records for predicting the HLT during a fumigation. The objective of this study was to explore the feasibility of using the superposition method for predicting HLTs by conducting fumigation experiments in a physical model silo. The superposition equation describes the total gas leakage rate from a structure in terms of prevailing wind speeds (U), temperature differences between inside and outside of the structure □ ($\Delta T$), and the effective leakage area of the structure ($A_L$). Fumigations were performed in a 228.5 l silo. Carbon dioxide at concentrations below 10,000 ppm was used as a tracer gas representing the fumigant. The pressure-flow pressurization test was performed before each fumigation in order to determine the effective leakage area. Two fumigation experiments were conducted. The purpose of the first experiment was to determine the wind ($C_w$) and stack ($C_s$) coefficients of the silo which were found to be $1.240\times10^{-3}$ $(L/s)^2/cm^4$-$(m/s)^2$ and $1.325\times10^{-3}$ $(L/s)^2/cm^4$-K, respectively. In the second experiment, fumigations were performed with prevailing wind speeds fixed at U = ~2.00, ~2.50 and ~4.50 m/s, and temperature differences fixed at $\Delta T$ = ~5.50, ~7.50, ~9.50 and ~11.00°C (i.e., 12 conditions) with three replicates for each condition. The recorded concentration decay curve of each fumigation was fitted with the first-order kinetic equation in order to determine the actual HLT ($HLT_a$). The values of $HLT_a$ ranged from 3.21±0.47 to 6.71±0.62 h. Then, these $HLT_a$'s were compared with the HLTs predicted by the superposition equation ($HLT_p$). The differences between $HLT_a$ and $HLT_p$ were less than 15.70% for all experimental conditions, and the relationship between the two could be explained by a straight line with a slope close to unity ($R^2$ = 0.894). It can be concluded that the superposition method was able to accurately predict fumigation HLTs of the 228.5 l model silo and thus its feasibility for HLT predictions in larger-scale fumigation should be further explored.

Keywords: fumigation, superposition method, half-loss time

## 1. Introduction

Efficacy of a structural fumigation depends on fumigant concentrations and exposure time, but oftentimes continuously maintaining high levels of fumigant concentrations is not feasible and long exposure time is not available. Thus, optimization of the fumigation process requires that the fumigant leakage rate (i.e., half-loss time, HLT) is estimated in advance so that a proper amount of the fumigant (i.e., dose) is precisely determined and released. In the current precision fumigation practices, HLT is 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 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 26h. A computer simulation fumigation study by Cryer (2008) which included only the surrounding wind factor indicated a similar finding. In addition to weather conditions, Chayaprasert and Maier (2010) showed that sealing quality of the structure also affects the fumigant leakage rate. The standardized pressure-flow (P-Q) pressurization test, also known as the blower door test, is usually used for quantification of air-tightness of buildings (ASTM, 1996). For calculating air infiltration 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). Fumigant leakage is linked to the infiltration process. Thus, the pressurization test and superposition method could be applied for predicting the HLT. Chayaprasert et al. (2008a) evaluated the HLT prediction accuracy of the superposition method against the validated Computational Fluid Dynamics (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 fumigation time 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 physical fumigation experiments were conducted in their study. As a result, the objective of the present study was to further explore the feasibility of using the superposition method for predicting HLTs by conducting fumigation experiments in a physical model silo.

## 2. Materials and Methods

### *2.1. Theoretical Calculations*

The HLT of a particular fumigation job can be adequately described using the first-order kinetic approximation (Cryer and Barnekow, 2006);

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

$C_t$ is the current concentration ($g/m^3$) and $C_i$ is the initial concentration ($g/m^3$). The elapsed exposure time t and HLT are expressed in hours. Via the derivation of the species transport equation, Chayaprasert (2007) showed that HLT (h) is associated with the total volumetric gas leakage rate (i.e., infiltration rate) ($m^3/s$), Q;

$$HLT = \frac{V}{Q}\frac{\ln(2)}{3{,}600} \tag{2}$$

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 $Q_s$, respectively, are determined separately and the total volumetric gas leakage rate is calculated as the square root of sum of the two (ASHRAE, 2001);

$$Q = \sqrt{Q_s^2 + Q_w^2} = \frac{A_L}{1{,}000}\sqrt{C_s \Delta T + C_w U^2} \tag{3}$$

$C_s$ 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 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 characterized by the size, shape and leakage openings of the structure. The effective leakage area, $A_L$ ($cm^2$), is calculated as (ASHRAE, 2001);

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

$\rho$ is the air density (kg/m$^3$), $C_D$ is the dimensionless discharge coefficient, and $\Delta p_r$ is the reference pressure difference (Pa). Note that $C_D$ and $\Delta p_r$ 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), indicate gas-tightness characteristics of the structure. These two constants are determined from the pressure-flow rate relationship of pressurization test in which the pressure difference between the inside of the tested structure and the natural barometric pressure, $\Delta p$ (Pa), is incrementally increased using a blower fan(s) operating at different constant air flow rates, q (m$^3$/s):

$$q = b(\Delta p)^n \qquad (5)$$

As a result, if the weather conditions, stack and wind coefficients, and volume and effective leakage area of the structure are known, the HLT of a fumigation job can be predicted by substituting Eq. 3 into Eq. 2:

$$HLT = \frac{V}{\frac{A_L}{1,000}\sqrt{C_s\Delta T + C_w U^2}}\frac{\ln(2)}{3,600} \qquad (6)$$

*2.2. Experimental Plan*

The equipment used to conduct fumigation experiments is assembled such that the factors influencing the HLT, namely wind speed, inside-outside temperature difference, and effective leakage area, could be controlled (Fig. 1). The model silo was a 228.5 l polypropylene tank. The tank was completely sealed except for four small holes (numbers 1–4 in Fig. 1) that were intentionally drilled. At each of the holes, a push-in pneumatic fitting for a tubing diameter of 6 mm was installed. Two of these fittings were used only for connecting pressurization test equipment and were sealed off during fumigation experiment. The unsealed fittings represented leakage areas on the silo. Carbon dioxide ($CO_2$) at concentrations below 10,000 ppm was used as a tracer gas representing the fumigant and its concentrations were recorded at 30s intervals using $CO_2$ data loggers (CO210, Extech Instrument Corp., Nashua, New Hampshire, USA). Speed of the wind impinging the silo was maintained constant throughout each replicate of fumigation using an electric blower operating at a fixed rotational speed. Different wind speeds were achieved by varying the distance between the blower and the silo. Similarly, constant temperature differences between inside and outside of the model silo were obtained by means of an electric heater and temperature controller. Wind speed and temperature were measured by a hot-wire anemometer (Climomaster Model 6531, Kanomax Japan Inc., Osaka, Japan) every 10s and $CO_2$ data loggers every 30s, respectively.

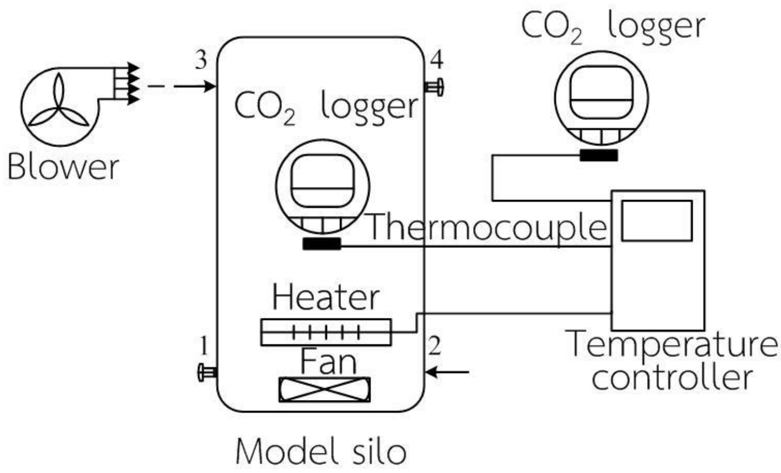


**Figure 1** Equipment setup for fumigation experiments in the model silo.

In this study, two experiments were conducted. In each experiment, fumigations were performed in the 228.5 l model silo at various combinations of fixed wind speeds and temperature differences. The goal of the first experiment was to determine the values of the stack and wind coefficients of the model silo. Once these values were known, the second experiment was conducted with an aim to illustrate that HLTs predicted by the superposition method (i.e., equation 6) and those observed from measured gas concentrations were comparable. The model silo was pressure-tested at $\Delta p$ of 100, 150, 200, 250 and 300 Pa before each fumigation and the effective leakage area of the silo for that particular fumigation was then calculated.

Assuming zero wind speed, Eq. 6 can be re-arranged as:

$$C_s = \frac{1}{\Delta T}\left(\frac{1{,}000}{A_L}\frac{V}{HLT}\frac{\ln(2)}{3{,}600}\right)^2 \qquad (7)$$

Similarly, assuming zero temperature difference it can be re-written as:

$$C_w = \frac{1}{U^2}\left(\frac{1{,}000}{A_L}\frac{V}{HLT}\frac{\ln(2)}{3{,}600}\right)^2 \qquad (8)$$

In this first experiment of this study, three replicates of fumigations were conducted at four constant wind speeds (U = ~1.6, ~2.0, ~2.5 and ~4.0 m/s) without temperature differences ($\Delta T$ = 0°C), and at four constant temperature differences ($\Delta T$ = ~5.6, ~8.5, ~10.4 and ~11.9°C) without surrounding wind (U = 0 m/s). The HLT of each fumigation replicate was calculated by first normalizing the measured $CO_2$ concentration curve by the initial concentration and then fitting the normalized curve with Eq. 1. Notice that the temperature difference, wind speed and volume of the silo were obtained by measurements, and the pressurization test provided the value of the effective leakage area. As a result, the stack and wind coefficients for each fumigation could be calculated using Eqs. 7 and 8, respectively.

In the second experiment, three replicates of fumigations were conducted at combinations of three constant wind speeds (U = ~2.0, ~2.5 and ~4.5 m/s) and four constant temp differences ($\Delta T$ = ~5.5, ~7.5, ~9.5 and ~11.0°C) (i.e., 12 conditions). The calculation of the HLTs of the measured $CO_2$ concentration curves was the same as in the first experiment. The HLT for each fumigation as predicted by the superposition method was also calculated using Eq. 6.

## 3. Results and Discussion

The results of the first experiment, which were used for determining the wind and stack coefficients of the model silo, are summarized in Tables 1 and 2, respectively. As the effective leakage area, $A_L$, is a property of the model silo, the increase of its values (from 0.0504 to 0.0605 $cm^2$ in Table 1 and from 0.0603 to 0.0709 $cm^2$ in Table 2) was due to weakening sealing quality and was not related to the faster wind speeds or the greater temperature differences. As the wind speed and temperature difference increased, the HLT decreased. Note that the coefficients of determination, $R^2$, associated with all curve fitting calculations in the first experiment were greater than 0.990. The resulting wind and stack coefficients were in ranges of $1.08 \times 10^{-3}$ – $1.41 \times 10^{-3}$ $(L/s)^2/cm^4$-$(m/s)^2$ and $1.20 \times 10^{-3}$ – $1.52 \times 10^{-3}$ $(L/s)^2/cm^4$-K, respectively. As the wind and stack coefficients are a function of the size, shape and leakage openings of the silo, given that these properties essentially did not change between fumigation conditions the values of the wind and stack coefficients were expected to remain unchanged, regardless of the fumigation conditions. A one-way ANOVA was conducted on each of the wind and stack coefficients. The ANOVA results indicated that there were no significant differences in the average wind coefficients as well as in the average stack coefficient ($P = 0.05$). Thus, the average of all $C_w$'s determined from the first experiment, which was $1.240 \times 10^{-3}$ $(L/s)^2/cm^4$-$(m/s)^2$, was considered the wind coefficient of the model silo. In a similar manner, the stack coefficient of the silo was found to be $1.325 \times 10^{-3}$ $(L/s)^2/cm^4$-K.

**Table 1** Result summary of the first experiment (average±SD)[a] for determining the wind coefficient, $C_w$, of the model silo.

| U (m/s) | $A_L$ ($cm^2$) | HLT (h) | $C_w$ ($\times 10^{-3}$) ($(L/s)^2/cm^4$-$(m/s)^2$) |
|---|---|---|---|
| 1.57±0.03 | 0.0504±0.0005 | 17.20±0.74 | 1.08±0.07 |
| 2.02±0.04 | 0.0535±0.0035 | 11.64±1.18 | 1.29±0.23 |
| 2.51±0.11 | 0.0526±0.0049 | 9.93±0.50 | 1.17±0.04 |
| 4.06±0.08 | 0.0605±0.0049 | 4.89±0.38 | 1.41±0.04 |

[a]Average and SD of three replicates.

**Table 2** Result summary of the first experiment (average±SD)[a] for determining the stack coefficient, $C_s$, of the model silo.

| ΔT (°C) | $A_L$ ($cm^2$) | HLT (h) | $C_s$ ($\times 10^{-3}$) ($(L/s)^2/cm^4$-K) |
|---|---|---|---|
| 5.64±0.96 | 0.0603±0.0001 | 9.16±0.18 | 1.20±0.25 |
| 8.49±0.08 | 0.0682±0.0034 | 6.55±0.59 | 1.20±0.11 |
| 10.41±0.67 | 0.0705±0.0005 | 5.31±0.03 | 1.38±0.11 |
| 11.90±0.09 | 0.0709±0.0032 | 4.66±0.32 | 1.52±0.02 |

[a]Average and SD of three replicates.

Fig. 2a shows normalized $CO_2$ concentration curves each of which was recorded from one replicate of the second experiment at relatively the same wind speed (U = ~4.5 m/s) with different constant temperature differences (ΔT = ~5.5, ~7.5, ~9.5 and ~11.0°C). Fig. 2b shows similar curves at relatively the same temperature difference (ΔT = ~7.5°C) with different constant wind speeds (U = ~2.0, ~2.5 and ~4.5 m/s). The effects of both wind speeds and temperature differences on fumigant leakage rates can be observed in these figures. With relatively unchanged wind speeds of 4.45 – 4.53 m/s, as the temperature difference increased from 5.61 to 11.86°C, the HLT decreased from 3.90 to 3.04 h. While the temperature difference remained around 7.5°C, the HLT decreased from 5.35 to 3.53 h as the wind speed increased from 2.03 to 4.48 m/s. However, notice that in Fig. 2b when U = 2.03 m/s and ΔT = 7.18°C, the concentration curve had a shorter HLT (4.55 h) as compared to the HLT (5.35 h) of the curve associated with U = 2.61 m/s and ΔT = 7.83°C. The fact that a greater wind speed and higher temperature difference resulted in a longer HLT could be attributed to a smaller effective leakage area. In the case of U = 2.03 m/s and ΔT = 7.18°C, the effective leakage area was 0.0697 $cm^2$ while in the opposite case it was 0.0627 $cm^2$.

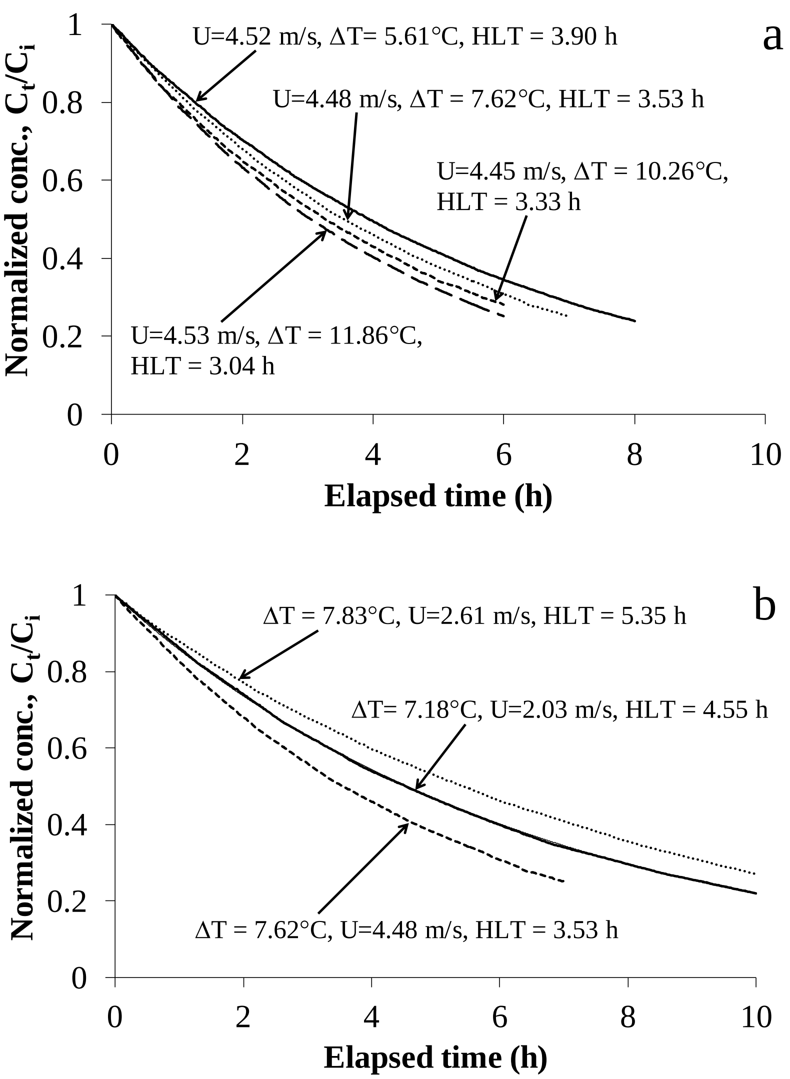


**Figure 2** Examples of decaying $CO_2$ concentrations due to (a) relatively the same wind speed (~4.5 m/s) with different constant temperature differences, and (b) relatively the same temperature difference (~7.5°C) with different constant wind speeds.

The results of the second experiment are summarized in Table 3. The HLTs determined from the measured concentrations, $HLT_a$, were between 3.21 – 6.71 h. The coefficients of determination, $R^2$, associated with all curve fitting calculations in the second experiment were greater than 0.990. Due to limitations of the blower and temperature control system, wind speeds and temperature differences below 2 m/s and 5°C, respectively, could not be generated, and thus $HLT_a$ above 7 h could not be achieved. Although best efforts were put into making the sealing quality of all experimental conditions consistent, the effective leakage area slightly varied in a range of 0.0633 – 0.0791 $cm^2$ (25% difference).

**Table 3** Result summary of the second experiment (average±SD)[a] comparing between the HLTs observed from measured gas concentrations, $HLT_a$, and those predicted by the superposition method, $HLT_p$.

| U (m/s) | ΔT (°C) | $A_L$ ($cm^2$) | $HLT_a$ (h) | $HLT_p$ (h) | %error |
|---|---|---|---|---|---|
| 2.03±0.02 | 5.60±0.09 | 0.0639±0.0036 | 6.71±0.62 | 6.16±0.35 | 7.95±3.16 |
| 2.61±0.09 | 6.10±0.07 | 0.0633±0.0009 | 5.40±0.28 | 5.40±0.19 | 5.20±3.68 |
| 4.51±0.03 | 5.38±0.23 | 0.0673±0.0020 | 3.83±0.07 | 3.63±0.10 | 5.20±2.79 |
| 2.02±0.01 | 7.32±0.27 | 0.0708±0.0011 | 4.58±0.08 | 5.12±0.10 | 11.72±3.49 |
| 2.64±0.04 | 7.40±0.49 | 0.0635±0.0010 | 5.26±0.22 | 5.11±0.14 | 2.87±1.98 |
| 4.43±0.06 | 7.73±0.09 | 0.0647±0.0013 | 3.60±0.12 | 3.66±0.10 | 1.65±0.50 |
| 2.01±0.05 | 9.27±0.16 | 0.0761±0.0016 | 3.80±0.06 | 4.39±0.11 | 15.70±1.10 |
| 2.45±0.04 | 9.66±0.33 | 0.0683±0.0017 | 4.25±0.05 | 4.53±0.09 | 6.48±1.91 |
| 4.44±0.01 | 9.99±0.31 | 0.0666±0.0036 | 3.43±0.23 | 3.41±0.20 | 1.80±0.38 |
| 2.00±0.00 | 11.20±0.30 | 0.0791±0.0014 | 3.48±0.06 | 3.95±0.04 | 13.51±1.74 |
| 2.46±0.02 | 11.63±0.07 | 0.0748±0.0053 | 3.82±0.39 | 3.90±0.27 | 2.96±4.10 |
| 4.48±0.10 | 10.36±2.56 | 0.0696±0.0048 | 3.21±0.47 | 3.25±0.44 | 2.67±2.93 |

[a]Average and SD of three replicates.

The %error of prediction in Table 3 was calculated as:

$$\%error = \left| \frac{HLT_a - HLT_p}{HLT_a} \right| \times 100$$

The %error values were in a range of 1.65±0.50 – 15.70±1.10% which mostly were below 10%. Fig. 3 is constructed using the average actual and predicted HLTs in Table 3. The relationship between the $HLT_a$ and $HTL_p$ could be explained by a straight line with a slope close to unity ($R^2$ = 0.894). Therefore, the superposition method could predict fumigant leakage rates with satisfying accuracy, suggesting their benefits to optimizing structural fumigation. Nevertheless, several simplifications and assumptions had to be made in this study. The model silo was empty and its size was excessively small. Commercial fumigations would be performed in silos filled commodities and uniform gas distribution could not be easily maintained. Natural wind most of the time varies both in speed and direction. Temperature of the ambient and inside the silo is constantly changing. The technique used for separately determining the stack and wind coefficients, $C_s$ and $C_w$, of the model silo may not be applicable for commercial settings. The superposition method should be further tested under conditions where these simplifications and assumptions are omitted.

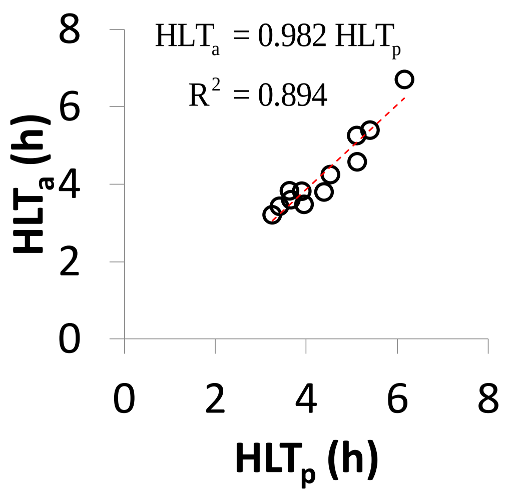


**Figure 3** Accuracy of the superposition method for predicting the HLT of fumigations in the 228.5 l model silo.

## 3. Conclusions

Application of the superposition method for prediction of fumigation HLTs in a 228.5 l model silo were investigated. Two fumigation experiments were conducted. The stack and wind coefficients of the model silo were determined in the first experiment. In the second experiment, fumigations were performed at 12 combinations of fixed wind speeds and temperature differences. The actual HLTs ranged from 3.21±0.47 to 6.71±0.62 h. The superposition method could predict fumigant leakage rates with satisfying accuracy, suggesting their benefits to optimizing structural fumigation. The differences between the actual and predicted HLTs were less than 15.70%. In addition, the relationship between the two could be explained by a straight line with a slope close to unity ($R^2$ = 0.894). However, this method should be further tested in larger-scale fumigations under natural weather conditions.

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