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Improving Structural Fumigation from Engineering Perspectives

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Abstract: Seven sulfuryl fluoride (SF) and one MB fumigation monitoring experiments were conducted as part of regular fumigations in three flour mills. In addition to fumigant concentrations, the environmental conditions both inside and outside of the fumigated facilities were monitored during the experiments. These results showed variability in the fumigation-related parameters that had substantial impact on the success and effectiveness of each fumigation.

A CFD model was constructed based on the flour mill as an analysis tool for prediction of fumigant distribution and leakage during the fumigation process. The data from one of the fumigation experiments was used to validate the CFD model. Given the same environmental conditions and fumigation practices, the model was able to reproduce a fumigant leakage rate (i. e., Half-Loss Time or HLT) and an achieved dosage value (i. e., Ct product) similar to those observed during the actual fumigation. Thus, it was considered validated.

The validated model was used to perform eleven fumigation simulations under weather conditions of the same time period of different years (1996 – 2006). Although the simulated fumigations were performed for the same time period, year-to-year variations in weather conditions caused significantly different HLT predictions. In extreme cases, the HLT prediction can be more than 100% different (from 10.7 to 23.3 hours), yielding a difference in the achieved Ct products by more than 70% (from 476 to 840 g · h/m^3). These results implied that fumigators should quantify the effectiveness of temporary structural sealing in order to verify HLT before a fumigation, minimizing fumigant use.

An automatic fumigation monitoring and decision support system was developed. The system consists of a purge pump, port selection panel, valve control unit, gas concentration sensor, laptop computer, and decision support program. Although the regulation of dosage rate to maintain the desired gas concentration still has to be manually done by the fumigator, the monitoring and decision support system helps prevent over dosing, reduces error and risk from human mistakes, and increases the success rate of fumigation.

Key words: structural fumigation, half – Loss time, computational fluid dynamics (CFD), flour mill, monitoring system

Introduction

The phase-out of methyl bromide (MB) as the major fumigant for use in structural fumigation has warranted the industry to seek for alternative pest control measures. We define structural fumigation as fumigation performed to eradicate pest infestations in permanent enclosures (portions of and whole buildings, industrial facilities, warehouses, gas-tight chambers) that may be empty or contain goods versus fumigation of tarp-covered product stacks or of soils However, fumigation with MB alternatives is more costly and requires a higher level of stewardship to be economically competitive. Therefore, the key for successful adoption of these alternatives lies in the efficiency of its application during fumigation. Because it is not practical to perfectly seal the structure, the fumigation process can be optimized only if the dynamics of gas movement in the fumigated space and the effects of environmental conditions on the process are well understood.

In August 2004, researchers in the departments of Agricultural and Biological Engineering, Mechanical Engineering, and Entomology at Purdue University with funding from the USDA – CSREES Methyl Bromide Transition Program and in collaboration with industry partners initiated a research project with the aim to develop a comprehensive analysis tool, and an automatic monitoring and decision support system for structural fumigation. This paper summarizes the findings and explores several possibilities

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and technologies to improve the structural fumigation process.

Fumigation Experiments

Seven sulfuryl fluoride (SF) and one MB fumigation monitoring experiments were conducted as part of regular fumigations in three flour mills. The primary goals of these experiments were to gain insights into the fumigation process and acquire data for the development and validation of a Computational Fluid Dynamics (CFD) model of the fumigation process. In addition to fumigant concentrations, the environmental conditions both inside and outside of the fumigated facilities were monitored during the experiments. A weather station, which was located on the mill's roof, monitored barometric pressure, wind speed and direction, temperature, relative humidity (RH), and solar radiation. Inside each mill, a 3D anemometer monitored the inside gas velocity, a pressure sensor measured the hydrostatic pressure, six temperature/RH loggers obtained the temperature and RH profiles along the height of the mill, 24 temperature cables measured the wall surface temperatures. A fumigant concentration sensor called Fumiscope® was used to monitor gas concentrations at 1 520 locations throughout the mill. Effects of sealing on the environmental conditions in the fumigated structure were observed in all experiments. The inside temperature was always higher than the ambient temperatures and vice versa for the inside relative humidity. These results showed variability in the fumigation-related parameters that had substantial impact on the success and effectiveness of each fumigation[1]. Therefore, being able to predict some, if not all, of these parameters will lead to the improvement of fumigation efficacy.

Structural Fumigation Modeling

The primary objective of developing the CFD model was to predict fumigant distribution and leakage during the fumigation process. The data from one of the fumigation experiments was used to validate the CFD model. Chayaprasert et al. [2] discussed the modeling methodology and results in detail. A commercial CFD solver, Fluent® (Fluent Inc., Lebanon, NH), was used to construct two flow models based on a reference flour mill. It was first used to construct a model of the flow outside the reference mill for predicting stagnation pressure profiles on the structure's walls created by prevailing wind and then construct a model of the fumigation process in the mill. The domain of the external flow model was set-up as a rectangular volume such that it included the mill building and surrounding structures. Several external flow simulations were conducted to determine average stagnation pressures on the mill's walls as a result of various wind speeds and directions. The relationship between average stagnation pressures and wind velocities was then formulated. Based on the formulated relationship, given the experimental wind data, the average stagnation pressures that would have occurred on the walls during the fumigation period could be estimated. Next, the average stagnation pressures were used as boundary conditions for the internal flow model. The total dimensions of the internal flow domain were 26.5 m × 34.4 m × 27.6 m, which contained rectangular solid volumes representing milling equipment such as roller mills, purifiers, sifters, pneumatic cyclones, tanks and tempering bins.

An example of the simulation results is shown in Fig 1b which illustrates the simulated concentration curves of all monitoring points in the first five floors. The primary discrepancies observed between the experimental data (Fig 1a) and the simulation data were in the fumigant introduction phase. In the simulation, there were fewer differences in the peak concentrations among the floors. This resulted in much less time for uniform gas distribution. The differences in the simulated concentrations at all locations were within 5 g/m^3 at the fourth hour, while the same occurred approximately at the sixth hour in the field trial. However, these discrepancies were not considered critical because on average the model was able to yield a HLT value close to the HLT derived from the experimental data. The HLT of the average simulated concentration curve was approximately 17 hours, which was essentially identical to the HLT of the average experimental concentration. The underpredicted concentration resulted in underprediction of the Ct product. At the time of unsealing, the achieved Ct products of the experimental and simulated data were approximately 950 and 850 $g \cdot h/m^3$, respectively, or a difference of 10.5%.

Based on the predicted HLT and Ct results, the CFD model was considered valid. The effects of fumigation variables such as wind speed and direction, capacity and placement of circulation fans, and fumigant release time on the efficacy of the fumigation process can be evaluated using the model. The results from the simulations will provide insight into understanding the dynamics of the structural fumigation process and help fumigators to correctly determine the amount of fumigant to be used, which in turn will yield increased efficacy and more successful fumigations.

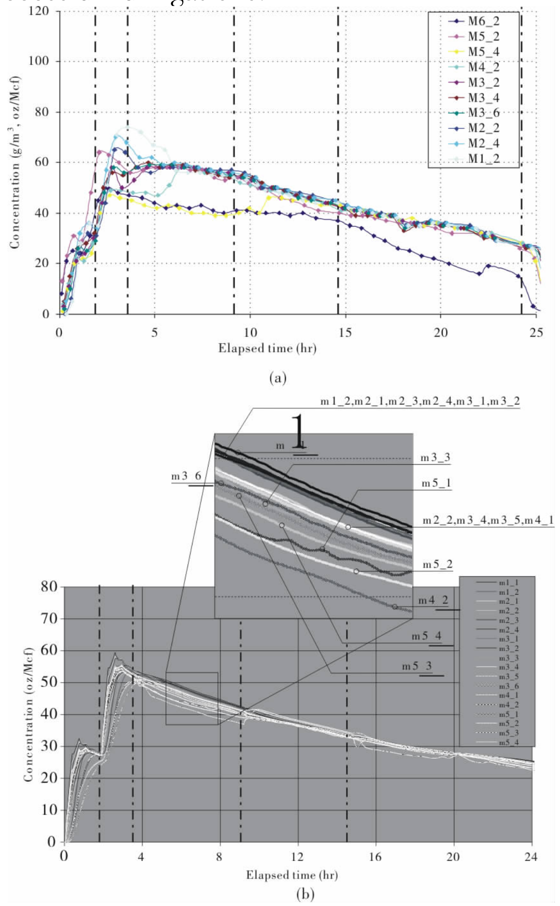

Fig. 1 (**a**) **Sulfuryl fluoride concentration data om the fumigation experiment.** (**b**) **Concentrations obtained from the internal flow model.**

Simulations of Eleven – Year Fumigations

The previously discussed CFD model was used to evaluate the effect of multi-year weather conditions on the gas leakage rate (i. e., HLT) and the Ct product during structural fumigation in the reference flour mill. Chayaprasert et al.[3] provided a complete discussion of the simulation setup and results. Eleven SF fumigation simulations were performed using 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 the 4th of July and lasted 24 hours. Hourly average historical weather data collected at the Indianapolis International Airport were used in the simulations. For all eleven simulations, the fumigation practices (e. g., sealing quality, fumigant releases, fumigant introduction and monitoring locations) were assumed to be the same. One fumigant introduction site was located around the middle area of each floor. At each introduction site, a circulation fan (2.71 m^3/s) was placed. A total of 226.8 kg of SF was released into each floor of the mill. The first half (113.4 kg) was released at the beginning of the fumigation and the second half was released approximately two hours later. The fumigant concentrations were monitored at 18 locations distributed throughout the mill.

Although the simulated fumigations were performed with the same temporary structural sealing quality for the same time period of the 11 years, the year-to-year variations in the weather conditions caused differences in initial concentrations, HLTs and Ct products. In extreme cases, the initial concentration was almost 20% different (from 54.3 to 44.6 g/m^3) and the HLT was more than 100% different (from 10.7 to 23.3 hours), yielding a difference in the achieved Ct products by more than 70% (from 476 to 840 $g \cdot h/m^3$). This means that for a given structure even though the fumigator could maintain the same sealing quality for every fumigation, the difference between the HLT predicted based on past fumigation data and the actual HLT observed during the current fumigation could be substantial. The fumigator would either overdose in the case of underpredicted HLT or have to intermittently release additional fumigant in the case of overpredicted HLT, resulting in a non-optimized fumigation process. As a result, past fumigation data should not be the primary means for evaluating the effectiveness of sealing and the effectiveness of temporary structural sealing should be measured under controllable conditions. One standardized method used by the HVAC industry for measuring building air-tightness is the pressurization test, also known as the blower door test[4,5]. In addition, a calculation procedure, in which the result of the pressurization test is incorporated, for air leakage rates due to weather conditions has also been suggested[4]. The pressurization test and this calculation procedure could be directly applied to the prediction of HLT and Ct product, given weather forecasts for the planned fumigation period. Therefore, the fumigation performance could be substantially improved.

Automatic Fumigation Monitoring and Decision Support System

Monitoring gas concentrations for the entire fumigation duration is a labor-intensive and tedious task. Therefore, it is typically not done on a continuous but rather on an intermittent basis (e. g., every 35 hours). However, best optimization of the fumigation process cannot be done without accurate HLT and Ct product estimations. Although prediction of half-loss time (HLT) and Ct product could be performed in advance with the application of the building pressurization test, the true HLT and Ct product can be observed only from the fumigant concentration levels inside the structure. Thus, the utilization of a fumigation monitoring system is another vital part to assure fumigation success.

Hardware Components

Fig 2 shows the hardware schematic of the automatic fumigation monitoring system. The system consists of a purge pump, port selection panel, gas concentration sensor, laptop computer and modular distributed I/O system. The purge pump (Model #2107CA20, Thomas Products Division, Sheboygan, WI) is used to draw sample gas through nylon tubing from the fumigated structure. The custom-made port selection panel is capable of handling up to 14 monitoring lines. It consists of one three-way and 14 two-way DC solenoid valves (Part #648T032 and #648T012, respectively, Neptune Research Inc., West Caldwell, NJ) each of which has an orifice size of 3.0 mm. The inlet of each valve is connected to a monitoring line and the outlet is attached to a manifold with its outlet connected to the Sulfuryl Fluoride Single Zone (SFSZ) Monitor (Spectros Instruments Inc., Hopedale, MA). The opening and closing sequence of the valves is controlled by the modular distributed I/O system called FieldPoint (National Instruments Corp., Austin, TX). The FieldPoint system consists of one interface module, one digital output module and one analog input module. The interface module, FP – 1000, is the primary module which communicates with the laptop computer through a RS – 232 cable. The digital output module, FP – DO – 401, sends 24 – volt signals to activate the solenoid valves. The analog input module, FP – AI – 110, reads gas concentrations in the form of electrical signals from the SFSZ monitor. The FieldPoint system actuates the solenoid valves according to a control program written in LabVIEW (National Instruments Corp., Austin, TX), which is part of the fumigation decision support (FDS) program discussed in the next section.

Software Program

The design of the FDS program was aimed at SF and red flour beetle eggs as the primary fumigant and target insect species/life-stage, respectively. However, the FDS program was developed on a generic platform such that it can be easily modified and customized to support other fumigants (e. g., methyl bromide or phosphine) and/or insect species/life-stages if the required dosage rate information for those particular fumigants and insect species/life-stages is available. The user specifies the number of fumigated volumes each of which is treated by the FDS program as a separate individual volume (i. e., assumes no interaction flow between volumes). Four fumigation parameters (i. e., temperature, HLT, exposure time, and size) are entered for each volume. The FDS program then provides the expected initial concentration, target Ct product, and required amount of SF. Gas concentrations in the fumigated volumes are monitored in cycles. For every new concentration reading taken, the FDS program performs a sequence of calculations to determine the Ct product that has been achieved up to the present time and to predict the Ct product that would be achieved at the end of the exposure time, i. e., the projected Ct product. As part of the fumigation control strategy, the FDS program compares between the projected and target Ct products. If the projected value is less than the target value, the FDS program displays an alarm message to the computer screen and provides a recommendation as to how much additional SF is needed and/or how long the exposure time needs to be extended in order to attain the target Ct product by the end of the fumigation.

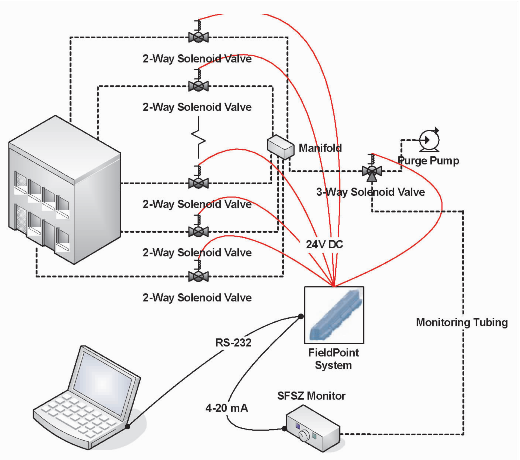

Fig. 2 Hardware diagram of the automatic fumigation monitoring system.

Conclusions

The CFD fumigation model serves as a simulation analysis tool that can be used to evaluate various "what if" fumigation scenarios, quantify the effects of weather conditions on HLT, and design possible fumigation strategies such that fumigation applications can be customized based on the prevailing site-specific conditions without the high cost of conducting full-scale fumigation experiments. Also, the established modeling methodology can serve as the basis for fumigation process modeling in any type of structure.

The experimental and simulation results showed that variations in the fumigant leakage rate from fumigation to fumigation can be substantial depending upon several factors (e. g. , sealing quality, weather conditions, etc.). Therefore, in order to optimize the fumigation process, using past fumigation data as the primary means for evaluating the effectiveness of temporary structural sealing quality and predicting HLT is not adequate. Predictions of fumigation performance should incorporate quantifiable sealing effectiveness and weather information for the planned fumigation period.

An automatic fumigation monitoring and decision support system was developed based on the technologies presently available to the fumigation industry. Although the regulation of dosage rate to maintain the desired gas concentration still has to be manually done by the fumigator, the monitoring and decision support system helps prevent over dosing, reduce error and risk from human mistakes, and increase the success rate of fumigation. Currently, the system operates on the tube-and-pump principle. The time and labor needed for setting up and disassembling the fumigation monitoring system would be reduced substantially, if wireless gas concentration sensors were available.

Acknowledgements

This study was funded by the USDA – CSREES Methyl Bromide Transition Program under project grant 2004 – 51102 – 02199 “Fumigation Modeling, Monitoring and Control for Precision Fumigation of Flour Mill and Food Processing Structures.” The cooperation, input and help of Mr. John Mueller, Mr. David Mueller, Mr. Peter Mueller and the staff of Fumigation Service & Supply Inc. , Indianapolis, Indiana has been greatly appreciated throughout this project. The cooperation of Dr. Suresh Prabhakaran, Mr. Marty Morgan and other staff at Dow AgroSciences, Indianapolis, Indiana, as well as the staff of several flour mills is also acknowledged.

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