DEVELOPMENT OF COMPREHENSIVE STRUCTURAL FUMIGATION MODELS

Watcharapol Chayaprasert*[1], Dirk E. Maier[1], Klein E. Ileleji[1], and Jayathi Y. Murthy[2]
[1]Agricultural and Biological Engineering Department, Purdue University, West Lafayette, IN 47907
[2]Mechanical Engineering Department, Purdue University, West Lafayette, IN 47907

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. However, fumigation with other 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 better optimized only if the dynamics of gas movement in the fumigated space and the effects of environmental conditions on the process are well understood.

This study was the first phase of an effort to develop an analysis tool for structural fumigation and a precision fumigation controller that can automatically apply and regulate fumigant gas during fumigation. The primary objective of this study was to develop Computational Fluid Dynamics (CFD) models for prediction of fumigant leakage and distribution during the fumigation process in a reference flour mill.

In order to collect experimental data necessary for validating the CFD models, a fumigation experiment was conducted as part of a commercial structural fumigation in a flour mill that has six floors with an approximate total volume of one million cubic feet. During the first four hours of the fumigation, four cylinders of Profume® (Sulfuryl Fluoride) were released into each floor of the mill. Each cylinder contained 125 lb of Sulfuryl Fluoride. 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 the mill, a 3D anemometer monitored the inside gas velocity, a pressure sensor measured the hydrostatic pressure, temperature/RH loggers obtained the temperature and RH profiles along the height of the mill, temperature cables measured the wall surface temperatures. Two Fumiscope®'s were used to monitor fumigant concentrations at 20 locations throughout the mill.

A commercial CFD solver, Fluent® (Fluent Inc., Lebanon, NH), was used to construct two flow models. 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 model development process was based on the hypothesis that an acceptable model should be able to reproduce concentration data that predicts Half-Loss Time (HLT) values and Ct products similar to those observed from experimental concentration data, given the same environmental conditions and fumigation practices. Thus, the models must be able to reproduce concentration data similar to those observed during the actual fumigation job.

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 of the internal flow model.

In the fumigation experiment, the sixth floor of the mill was sealed such that it was separated from the other floors. Assuming that the air pathways were perfectly sealed, the domain of the internal flow model included only the first five floors of the mill. In addition, it contained rectangular solid volumes representing milling equipment such as rollermills, purifiers, sifters, pneumatic cyclones, tanks and tempering bins. The total dimensions of the domain were 87 ft × 113 ft × 90.5 ft.

To model leakage, it was assumed that the leakage of fluid through all cracks on a wall can be equivalently represented by the leakage through an equivalent leakage zone (ELZ). An ELZ was a pressure boundary condition with an assumed area (effective leakage area) and a loss coefficient. The effective leakage area for the ELZ was arbitrarily chosen as a circle with a diameter of 1.4 ft. Five ELZs were placed on each of the north, east and west walls. Each ELZ was positioned at the middle of the wall on each floor. The entire south side of the mill was attached to a grain bulk structure and a packaging area. Therefore, it was assumed that there was no leakage through the south side of the mill. As a result, no ELZ was placed on the south wall. According to 2001 ASHRAE Fundamentals Handbook, in addition to the wind effect, another cause of building infiltration is the stack effect. Thus, at each simulation time step, the pressure value assigned to each ELZ was a summation of the average stagnation pressure (determined from the external flow model), which was different for different walls, and the stack effect pressure, which varied with the height of the ELZ. The calculation of the stack effect pressure followed the 2001 ASHRAE Fundamentals Handbook's guideline. Fumigant concentrations in the simulation domain were collected every 3 minutes at the same locations as in the actual mill.

An example of the simulation results is shown in Figure 1 which illustrates the simulated concentration curves of all monitoring points in the first five floors. The primary discrepancies observed between the field trial data (not shown) 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 the locations were within 5 oz/Mcf 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 as discussed in the next paragraph.

The average of all concentration curves in Figure 1 is plotted as the smooth solid curve in Figure 2a. The curve with markers shown in Figure 2a indicates average concentrations calculated using the experimental readings. Comparing the two average curves, most of the time the model slightly underpredicted the concentration levels. However, it was determined that the HLT of the simulated concentration curve was approximately 17 hours, which was essentially identical to the HLT of the actual mill. The Ct products (i.e., area under the concentration curve) corresponding to the concentration curves in Figure 2a are plotted in Figure 2b. The underpredicted concentration curve 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 oz-hr/ft^3, respectively, or a difference of 10.5%.

This research presented a methodology for using a commercial CFD solver, Fluent®, to model the fumigation process in a flour mill based on a data set collected at an actual fumigation site. The final achieved Ct product was underpredicted by 10.5%. Furthermore, the HLT values derived from the internal flow model result and the field trial data were essentially the same (17 hours). Therefore, the CFD models developed in this study were valid and the established methodology could be utilized for fumigation process modeling in any type of structure. Given weather conditions, the models can be used to predict fumigation characteristics such as fumigant movement paths, concentration distributions, and leakage rate. 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 are currently being evaluated. 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 fumigation jobs.

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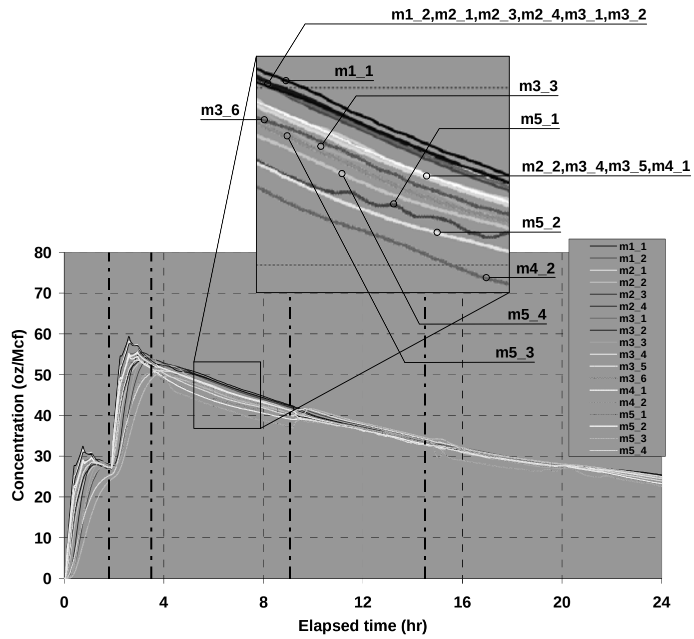
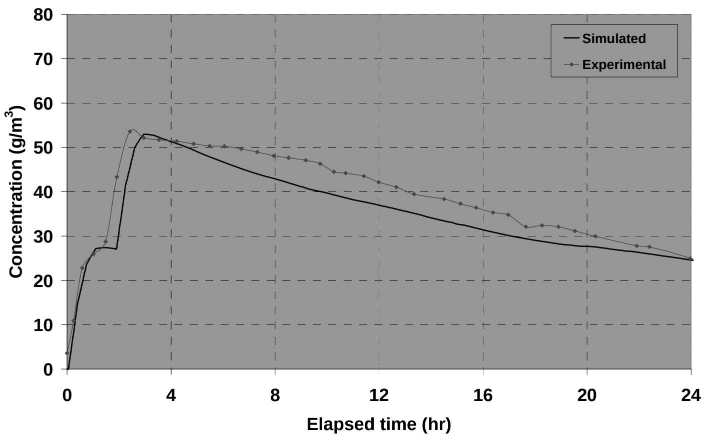
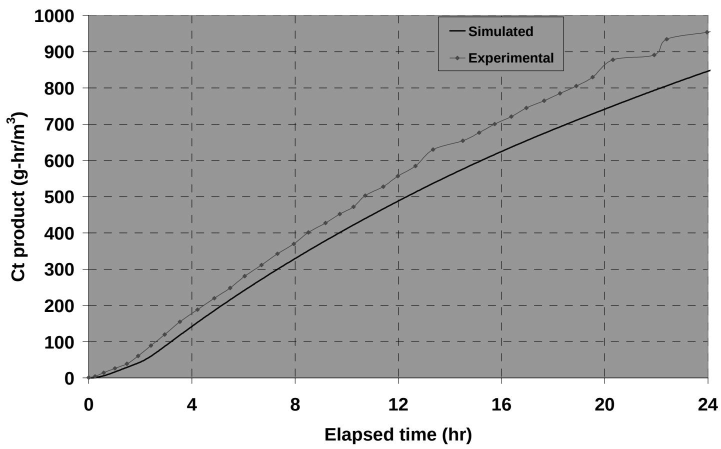


Figure 1. ProFume® concentrations obtained from the internal flow model.



(a)



(b)

Figure 2. Comparison between the fumigation trial and simulation results. (a) Average concentration plot. (b) Average Ct product plot.