Modeling phosphine distribution in grain storage bunkers

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Abstract

Stored grains are often protected from insect infestation with chemical insecticides and fumigants. Chemical grain protectants leave residues, while chemical fumigants normally do not. Fumigants can kill all insect life stages because the fumigant gas can reach pests by diffusion through the spaces between and into the grain kernels. The predominant fumigant used for the treatment of bulk-stored grain worldwide is phosphine. However, increasing resistance of insects to phosphine has been broadly observed. With increasing global market sensitivity to insecticide residues, improved pest management practices are needed to overcome phosphine resistance and pest management agents are needed that have low mammalian toxicity and high specificity to insects with no adverse environmental impacts. This study is investigating, through simulation modeling, more effective application methods for phosphine fumigant. Phosphine distributions in bulk storage structures (bunkers) during fumigations were modeled and predicted concentration profiles and the effect of wind phenomena were studied. Knowledge of fumigant movement in bulk storages will help in effective distribution of the phosphine fumigant, developing best management practices for prevention of phosphine-resistant insects, and extension of the effective use-life of phosphine and will be instrumental in keeping the grain export industry free from insect strains resistant to phosphine.

Keywords: phosphine fumigant, modeling, stored grain, bunkers, insects

1. Introduction

Australia's grain and oilseeds industry produces about 35 to 45 million metric tons of grain per year with an annual gross value of production of around 9 to 13 billion Australian dollars (ADA, 2014). Wheat is the major crop and the major export grain. About 60% of total wheat production is exported (ADA, 2013). To successfully compete in the world market, grain exporters must provide high quality product. One major factor in grain quality is the absence of insect infestation and damage.

Historically, grain exports in Australia have often been protected from insect infestation with chemical insecticides and fumigants (van Graver and Winks, 1994; Collins et al., 2001). Chemical insecticides (grain protectants) leave residues, while chemical fumigants normally do not. The increasing concerns over the resistance to grain protectants and the preference of markets for residue free grain (Collins, 1998) have motivated grain handlers and exporters to favor fumigants over protectants. Fumigants can kill all insect life stages because the fumigant gas can reach pests by diffusion through the spaces between and into the grain kernels. The predominant fumigant used for the treatment of bulk-stored grain in Australia and worldwide is phosphine due to its low price, ease of application, and minimal residue (Boland, 1984; Bullen, 2007; Chaudhry, 2000; Collins et al., 2001; Rajendran, 2007).

Stored grain protection in Australia has been dependent on the use of phosphine since the mid-1990s. Even though there are a number of chemical and non-chemical grain treatments that have been developed, some with specialized applications, none can match the use of phosphine (Collins, 2010). However, strong resistance to phosphine was first detected in Australia in the lesser grain borer, *Rhyzopertha dominica* in 1997 (Collins 1998), then in the sawtoothed grain beetle, *Oryzaephilus surinamensis* (L.) and the red flour beetle, *Tribolium castaneum* (Herbst) in 2000, in the flat grain beetle, *Cryptolestes ferrugineus* (Stephens) in 2007, and most recently in the rice weevil, *Sitophilus oryzae* (L) in 2009 (Collins et al., 2005; Collins, 2010). The frequencies of strong resistance detected in Australia remain low possibly due to the resistance mediated by two incompletely recessive genes that both need to be homozygous in an individual insect before the resistance is expressed (Collins, 2010). This lag provides an opportunity to research and develop strategies to manage this resistance.

Fumigations are ideally carried out in sealed grain storage structures. Uniform and fast application of fumigant to all parts of the grain storage is fundamental to effective pest management. However, little is known of the behavior of fumigants in grain storages (Collins, 2010). Fumigant sorption by the grain (Darby, 2008) and leakage from poorly sealed bins (Reed and Pan, 2000) resulted in sublethal concentrations of phosphine, which, over many years, has led to the widespread insect resistance observed in recent years.

The lesser grain borer, *R. dominica*, is the most difficult of the common grain insect species to kill with fumigants. Validated models of fumigations can be used to evaluate where and why sublethal concentrations occur during fumigation and to develop improved fumigation practices to ensure adequate concentrations of the fumigant throughout the storage facility. Singh et al. (1993) developed a 3-dimensional heat, mass, and momentum transfer model with species concentration for predicting fumigant concentrations in a rectangular domain. Lawrence et al. (2013a, 2013b) developed a 3-dimensional model that is not limited to rectangular domains and used it to predict fumigation concentration in cylindrical (vertical) silos. This model needs to be validated under a wider range of conditions, and can then be used to evaluate causes of fumigation failures and to develop best management practices to prevent the failures. Mat Isa et al. (2014) developed a 3-dimensional transport model for phosphine flow during grain fumigation in leaky cylindrical silos. Although the model was not validated, it included gas sorption and insect extinction models which were empirically based.

Previously, there was no validated model for phosphine flow inside horizontal grain storages (bunkers). This study is investigating, through simulation modeling, a more effective application of phosphine fumigant in grain storage bunkers. The specific objective is to model phosphine distribution inside a grain storage bunker using computational fluid dynamics. The current simulations use a 2-dimensional model of the 30-m wide (by 120-m long) grain storage bunker with peak height of 8.5m. Knowledge of fumigant movement in bulk storages will help in effective distribution of the phosphine fumigant, developing best management practices for prevention of phosphine-resistant insects, and extension of the effective use-life of phosphine and will be instrumental in keeping the grain export industry free from insect strains resistant to phosphine.

2. Materials and Methods

2.1. Grain Storage Bunker Model

A 30-m wide with peak height of 8.5m grain storage bunker was modeled in 2-dimension (Fig. 1) using computational fluid dynamics (CFD) (ANSYS Workbench with Design Modeler, Meshing, and Fluent, ANSYS Inc., Canonsburg, PA). The grain inside the bunker geometry was represented by porous zone. Field observations indicated that the wind-driven billowing tarpaulin on top of the bunker was a primary factor in fumigant distribution. In the field studies the fumigant gas was quickly transported from the injection point along the top surface of the grain, due to the tarpaulin billowing action, from where it slowly moved down through the rest of the grain mass (Darby, 2011). A 0.3-m thick non-porous zone was included in the model, under the tarpaulin and on top of the grain surface, to represent the effect of the billowing tarpaulin. Wind pressure was also modeled as driving air leakage along the bottom edge where the tarpaulin meets the side wall. The wind pressure at this leakage point helped drive the flow of fumigant and air along the non-porous zone under the tarpaulin and the fumigant then moved down through the rest of the grain. Air inlets were 0.075m and phosphine injection sites were 0.5m at both sides. An outlet was placed at the bottom center for this particular simulation model. Triangle mesh was used in ANSYS Meshing, which created 5705 nodes and 10746 elements for the model (Fig. 2).

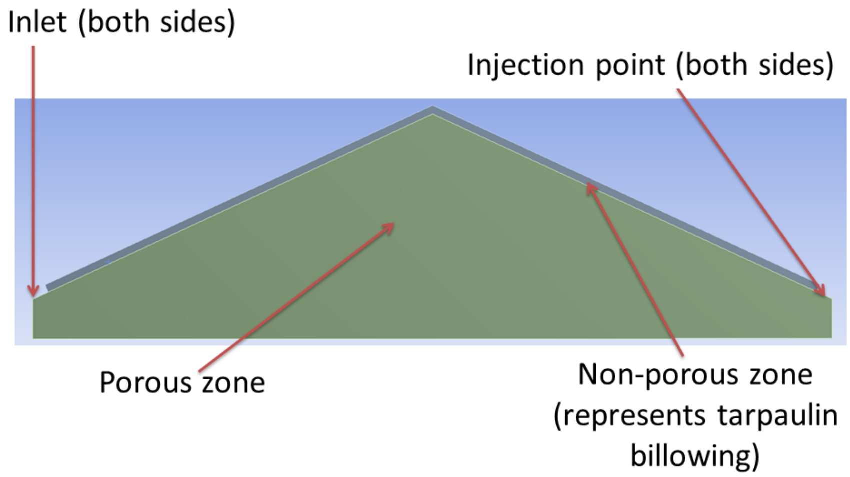

Figure 1 Grain storage bunker geometry in 2-dimension.

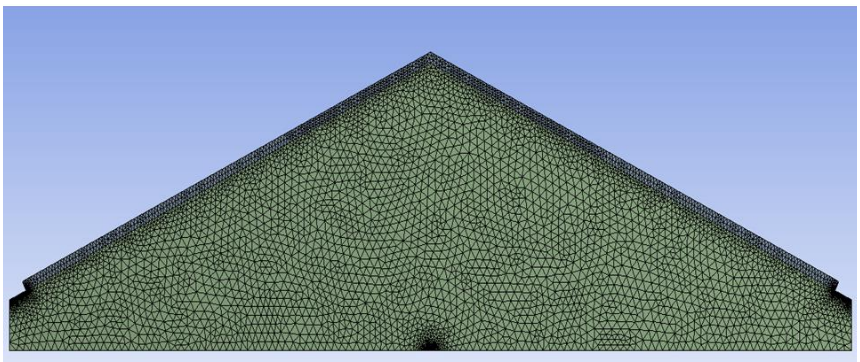

Figure 2 Grain storage bunker mesh in 2-dimension.

2.2. CFD Model Parameters

ANSYS Fluent was used to solve the transient species transport model. For the porous zone, a porosity of 0.396 for wheat (Molenda et al., 2005) and a computed viscous loss coefficient of $8.09 \times 10^7/m^2$ were used as inputs; the inertial loss coefficient was considered negligible. Materials and mixture property inputs are given in Table 1.

For this initial model, air inlets were given a fixed velocity of 30 m/s because the effect of wind on tarpaulin billowing was not yet known in this case. The phosphine injection points were given a fixed velocity of 5 m/s. The initial temperature was assumed 20°C (293.15 K) for both inlets. The walls were considered no-slip wall. The species mass fractions were assumed 1.0 for the phosphine injection points and zero for the air inlets.

Table 1 Materials and mixture input properties.

Parameter	Symbol	Unit	Wheat	Air	Phosphine (PH_3)	Mixture (Air-PH_3)
Density	ρ	kg/m^3	1300	incompressible-ideal-gas	1.379	incompressible-ideal-gas
Specific Heat	C_p	J/kg-K	1549	1006.43	1093	mixing-law
Thermal Conductivity	k	W/m-K	0.1402	0.0242	0.016	mass-weighted-mixing-law
Dynamic Viscosity	μ	kg/m-s		1.7894×10^{-5}	1.1×10^{-5}	mass-weighted-mixing-law
Molecular Weight	M	kg/kmol		28.966	33.997	
Mass Diffusivity	D	m^2/s		2.21×10^{-5}	1.59×10^{-5}	constant-dilute-approximation

3. Results and Discussion

Grain storage bunkers in Australia are not gastight storage. They do not have headspace like vertical silos and are characterized by a flexible covering tarpaulin that will billow substantially in the wind (Darby, 2011). The mechanism for distribution of phosphine is expected to be dominated by the billowing of the flexible tarpaulin and the lack of gastightness of the bunkers. Previous bunker fumigation field trials have shown that phosphine dispersal inside the bunkers is greatly affected by wind and tarpaulin billowing (Banks, 1981; Banks and Sticka, 1981; Yates and Sticka, 1984).

Figures 3 to 5 show the phosphine distribution as it propagates from the injection points from both sides of the bunker, towards the top of the grain stack surface, and finally spreads across the grain stack. These concentration profiles qualitatively follow the trend from experiments, which describes the initial distribution phase of phosphine concentrations involving dispersal over the grain stack surface, enclosed beneath the tarp; followed by penetration into the stack from these surface locations (Darby, 2011).

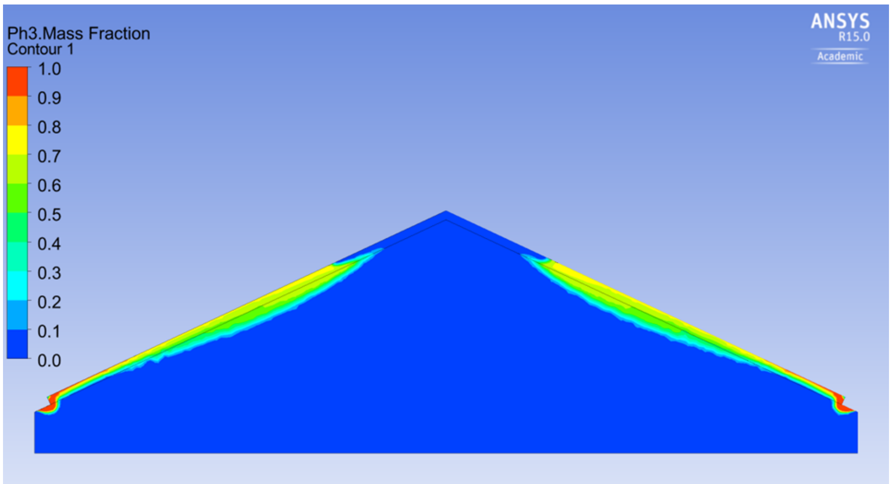

Figure 3 Phosphine distribution near the beginning of the simulation.

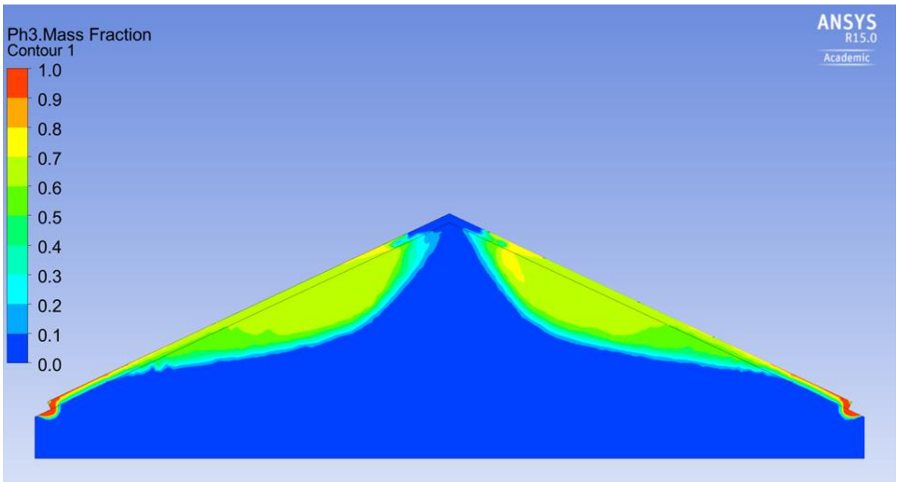

Figure 4 Phosphine distribution in the middle of the simulation.

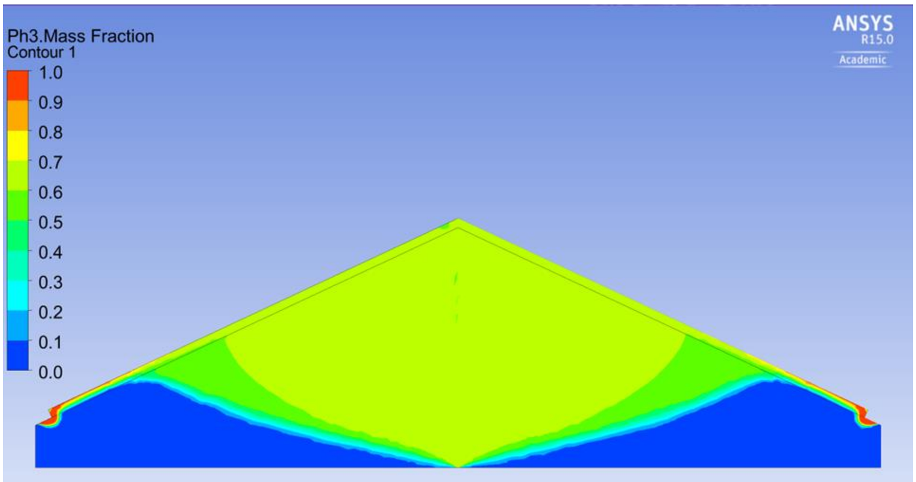

Figure 5 Phosphine distribution towards the end of the simulation.

4. Conclusions

Phosphine distribution inside a 2-dimensional grain storage bunker was modeled using computational fluid dynamics. During the initial distribution phase, phosphine distribution was characterized by increasing phosphine concentration dispersal over the grain stack surface, enclosed underneath the tarp. This initial phase was followed by penetration downward into the grain stack and phosphine reaching the majority of the bunker during the simulation.

This preliminary model has shown that the phosphine concentration profiles qualitatively follow the trend from experiments. Future simulations will involve quantifying the phosphine concentrations that are applied during fumigation, modeling different methods of phosphine application inside the grain bunkers, and looking at how the wind effect and tarpaulin billowing phenomena affect phosphine distributions in these cases. The 2-dimensional model will be extended to a 3-dimensional model of a bunker slice (20-m long) and then to a full-length (120-m long) storage bunker.

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