Fumigation modelling of hopper-bottom railcars

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Abstract: Bulk railcars are a common method of moving commodities in the United States. Allowances are given for the practice of treating railcars with fumigates during transit because the routes are limited access and not on public roads. The phosphine concentrations at the top varied with time with phosphine spiking over 1600 ppm and gradually settling to over 300 ppm at the end of the eight days. Total gas dosage was estimated as concentration × time (CT) over the eight days as 115,000 and 125,000 ppm × hr at the top of each railcar. These tests found significant phosphine penetration into the bulk at 2 m depth with ~ 380 ppm after two days and going down to ~ 260 ppm after eight days with the high phosphine treatment. Bioassays of both phosphine susceptible and resistant, *Rhyzopertha dominica* (F.), lesser grain borer, and *Tribolium castaneum* (Herbst), red flour beetle, were included at both the surface (0 cm), 25 cm and 60 cm below the surface. All insects, at all locations, were dead after eight days. The railcar and the fumigation treatments were additionally modelled with a CFD simulation approach. The simulation models were shown to provide estimates of the phosphine concentration and distribution which matched well the observed data, validating the computational fluid dynamic (CFD) approach as an efficient tool for future planning and analysis of similar fumigations.

Key words: phosphine, lesser grain borer, ref flour beetle, computational fluid dynamics, wireless sensors, mathematical modelling

Introduction

United States (US) agriculture produced 580 million metric tons of grains and oilseeds in 2021 and 556 million metric tons in 2020 (USDA-NASS, 2021) and rail is the predominate method for long distance transport of grain. During storage and transportation through these supply and distribution channels, infestation by stored product insects could potentially occur. Insect infestations can lead to contamination and reduced quality and have a significant economic cost to the food industry for controlling these pests (Agrafioti et al., 2020 a; b; Brabec et al., 2021). A common pest suppression method for bulk grain or packaged grain-based products is fumigation with phosphine. Phosphine treatments usually require several days of confinement to provide maximize control of insects, and it is important to maintain an adequate gas concentration during the treatment period (Agrafioti et al., 2018; 2020 a; Brabec et al., 2021).

The duration of the treatment depends on factors such as gas concentration, temperature, and phosphine-susceptibility of the insect species. Inadequate concentration-time (CT) due to low gas concentrations or poor gas containment can lead to minimal control of the insect populations and development of insect resistance. However, little information is available on the efficacy of rail car treatments, in contrast with other storage methods, such as containers and silos, where phosphine distribution and the concomitant insecticidal effect have been quantified (Agrafioti et al., 2018; 2020 a; b; 2021).

Different mathematical and computational fluid dynamic (CFD) models have been developed for phosphine fumigation studies. Isa et al. (2016) modelled fumigant distribution in leaky grain silos which used fan-forced fumigation. Agrafioti et al. (2020 b) combined the distribution of phosphine within specific fumigated structures with insect mortality models. Also, Agrafioti et al. (2021) modelled the distribution of phosphine gas in metal shipping containers, illustrating the parameters that may affect gas distribution. There are several reports for other types of storage structures, such as food processing facilities (Chayaprasert et al., 2006), bulked grains (Plumier et al., 2018), and bunkers (Boac et al., 2014). To the authors knowledge, there is inadequate information regarding modelling the distribution of phosphine in railcars.

In this context, the major objective of this study is to collect fumigation data from railcars during transit in commercial applications, for which there are not many data available. In addition, a secondary objective of this work was to model a hopper bottom railcar loaded with product and estimate fumigation outcomes after 4-8 days of transit.

Materials and methods

Hopper bottom railcars and fumigation

Hopper bottom railcars were being used at a corn processing facility to ship corn grits to customers (Figure 1 a). A hopper bottom railcar has the capacity to carry over 95 tons of products. A railcar was monitored in August of 2019 and a second railcar was monitored in September 2019. Each railcar was given a dose of tablets as supplied with the pre-packaged product (PHOSTOXIN® Tablet Prepac, Degesch American, Richmond, VA, USA).

Fumigation monitoring

Monitoring railcars was accomplished using Centaur phosphine sensing electronics and software operating in data logging mode. The sensing units (Figure 1 b) were deployed and spaced along the top of the railcar and measured phosphine concentration and temperature every 4 hours for a duration exceeding 14 days. The accuracy of the sensors has been successfully evaluated by Brabec et al. (2019).

Phosphine penetration into corn grits (barrel experiments)

Deeper access into the corn grits was not available during the railcar fumigations with the electronic sensing units. Sub-experiments were done to estimate phosphine distribution deeper using columns of corn grits stored in long tubes fabricated from three barrels (Figure 1 c). These tests were conducted at USDA-ARS. The two columns were each comprised of three stacked barrels and had a total height of 2.4 m and a diameter of ~ 58 cm. Each column contained ~ 500 kg of corn grits and was filled to ~ 18 cm of the top. Two levels of phosphine were tried, and each treatment was repeated three times.

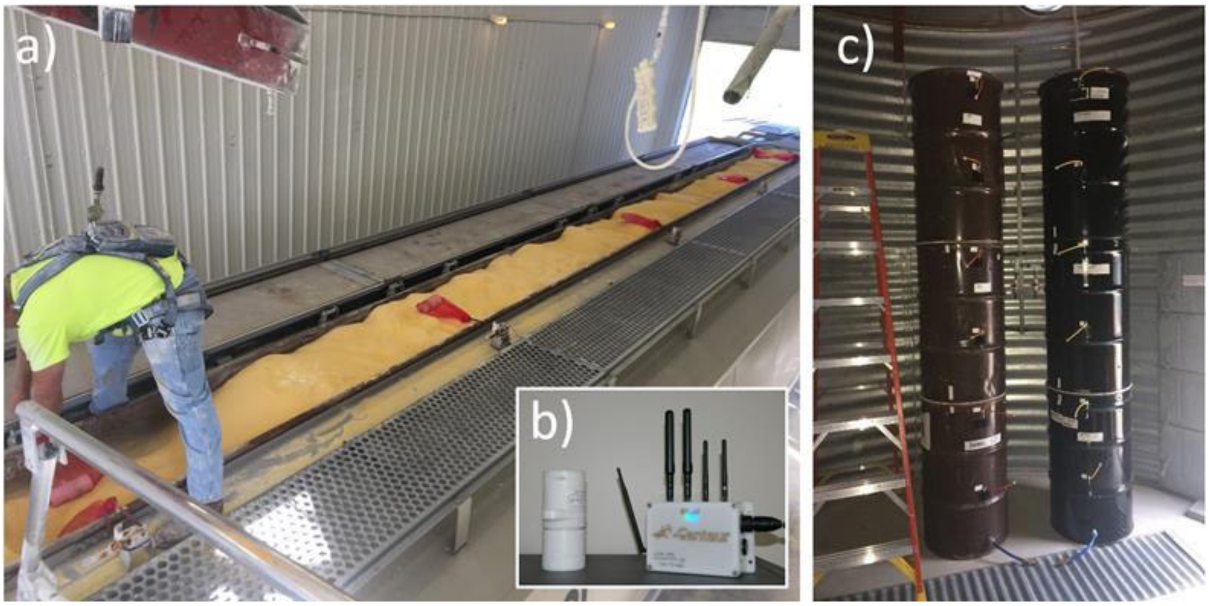

Figure 1. a) Top of railcar holding the corn grits for shipment and the Centaur sensing units placed at the ends and middles of the top (red bags); b) Centaur sensing unit and gateway; c) columns of barrels used to test potential phosphine distribution deeper into the corn grits.

Insect bioassays

Two species of insects were used in the barrel experiments, *Tribolium castaneum* (Herbst), the red flour beetle (Coleoptera: Tenebrionidae) and *Rhyzopertha dominica* (F.), the lesser grain borer (Coleoptera: Bostrichidae). For each insect species two different strains were used, a phosphine resistant and a phosphine susceptible. All beetles used in experiments were collected and placed into plastic bioassay tubes with 1.0 mm holes with 1.0 mm holes to facilitate gas penetration. The bioassay tubes were inserted into the corn grits at three locations using a push-rod. After each fumigation trial, the number of beetles alive, affected, or dead were counted (Scheff et al., 2019).

Modelling of railcar fumigation

Modelling of the railcar was accomplished using a CFD model developed by Centaur Analytics, Inc. Detailed descriptions of the model equations for air velocity, temperature, phosphine concentration, phosphine sorption, and their implementation in porous media were presented in detail in Agrafioti et al. (2020 a). Also, the phosphine concentrations were used to estimate mortality of stored-product insects based on an earlier developed insect indicator function (Agrafioti et al., 2020 b). For improved simulation predictions, the ambient temperature, wind velocity, and solar radiation during the transit of the first railcar were considered as boundary conditions to the CFD model.

To solve the transport equations of the model, a discretizing procedure (meshing) of the complicated railcar (4.8 m height × 3.4 m width × 17.8 m long) geometrical was performed. For this study, the mesh used was structured (hexahedra) thus ensuring better accuracy.

Furthermore, the mesh resolution was increased near the walls to properly capture large gradients. The total number of grid cells was ~ 410,000.

Results and discussion

Railcar monitoring data

The top layers of the corn grits were monitored for over eight days (Figure 2). Both hopper-bottom railcars held phosphine gas at the top for the entire eight days. In one railcar, the phosphine was generated early and during days 1-3. For the other railcar, the phosphine generation was delayed a bit and had more generation during the middle of the cycle. Both railcars had spikes of phosphine generation which reached over 1600 ppm. By the end of the trip, the phosphine concentration had decreased to around 200-300 ppm. However, a measurement at the top of the commodity does not necessarily equal the phosphine concentration within the bulk commodity.

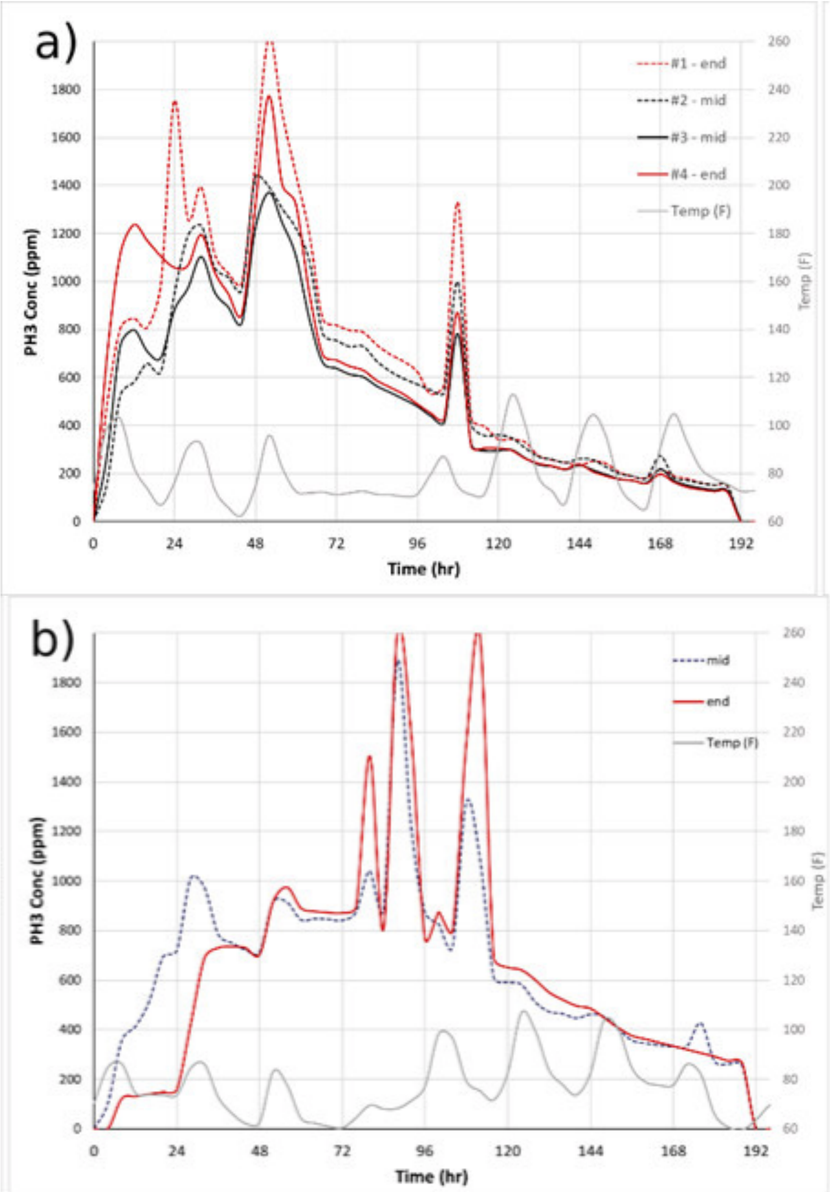

Figure 2. Fumigation monitoring data from two hopper-bottom railcars. The railcar on topt had four phosphine sensing units, while the railcar on the bottom had two phosphine sensing units. Temperature data was over laid at the bottom of each chart (grey line).

Phosphine penetration tests

As seen in Figure 3, although the phosphine at the top of the corn grits was over 1200 ppm, the phosphine in the corn grit was a gradient from ~ 600 ppm at 25 cm down to ~350 ppm at 2 m. After four days, the gas concentration in the bulk was level at ~ 380 ppm for the high treatment and ~ 180 ppm for the low treatment. Then after eight days, the phosphine concentration was about level at 300 ppm for the high treatment verse ~ 120 ppm for the low treatment at 2 m depth. Among all insect species and strains and all bioassay depths, there was 100 % mortality for those treated with phosphine gas for the eight-day trials.

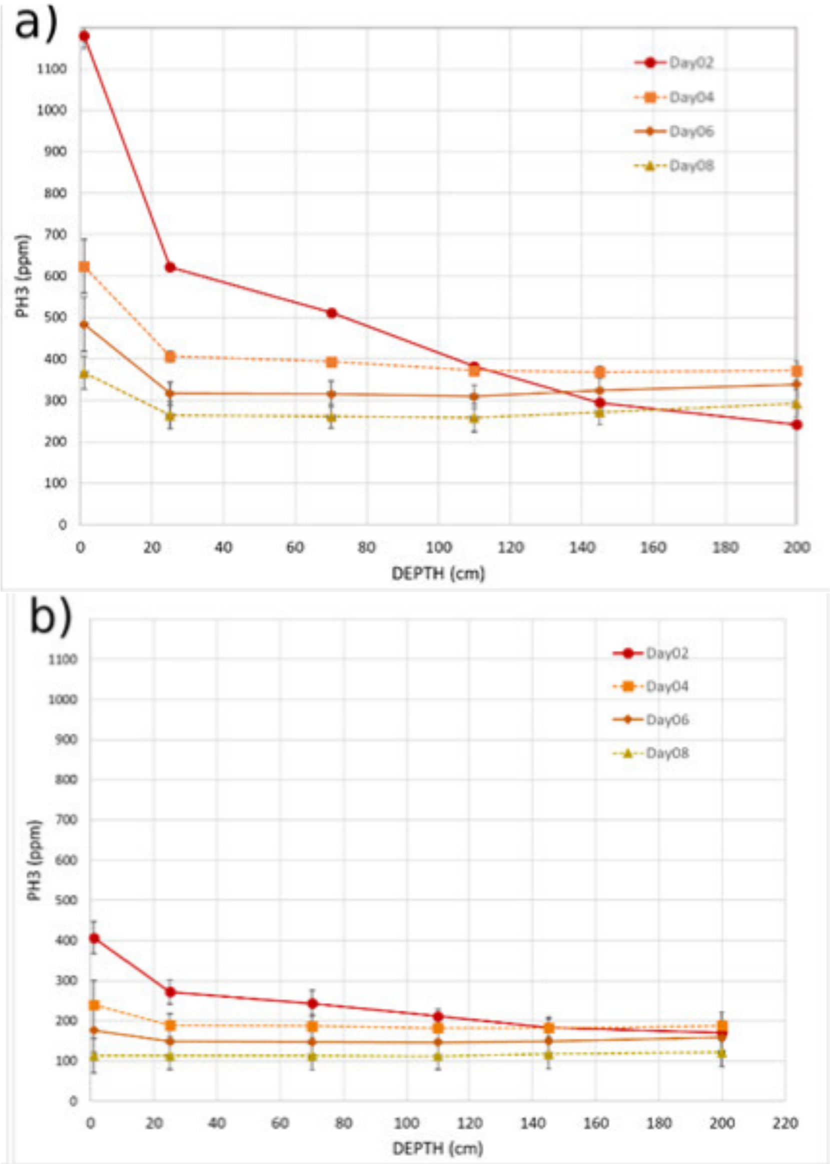

Figure 3. The high (a) and low (b) phosphine treatment in the column of corn grit experiments. The individual lines represent phosphine concentration data taken after two, four, six, and eight days of treatments.

Railcar fumigation modelling

To ensure the accuracy of the model in predicting the phosphine concentration, a comparison is made between railcar sensor data and the CFD model for the respective sensor positions. The CFD model predictions agree with the trends of the railcar data. Even the peak phosphine events were determined since the computational model considered variations from the ambient conditions. The median absolute error over the eight days was 89 ppm.

The overall performance of the CFD model was considered satisfactory, ensuring the validity of the phosphine concentration predictions for the entire container space as the ones presented in Figure 4. These models present the spatial distribution of phosphine concentration in a three-dimensional view at the end of the second and sixth day respectively. Early, the phosphine is concentrated in the head space of the railcar, while later, the phosphine is more evenly distributed throughout the commodity. Nonetheless, there is some non-uniformity in the lower regions of the rail car, particularly between the side walls and the core of the corn grits. This effect may be attributed to the air movements caused by the temperature differences between the ambient and grain. The model also predicted the insect mortality profiles at the end of the fumigation process. The areas near the top of the railcar reached lethal levels but the phosphine concentration was not sufficient to control the insects at the lower core of the corn grit. An exception lies near the outer layers where the model predicted that phosphine had penetrated deeper.

The results of the present study clearly show that the CFD fumigation model was successfully validated with hopper bottom railcars and that CFD modelling can provide the inferences necessary to plan a judicious fumigation strategy in in-transit grain fumigations.

Figure 4. Three dimensional profiles of the estimated phosphine concentration profiles after two days and six days. The concentration levels can be interpreted with the colour legend.

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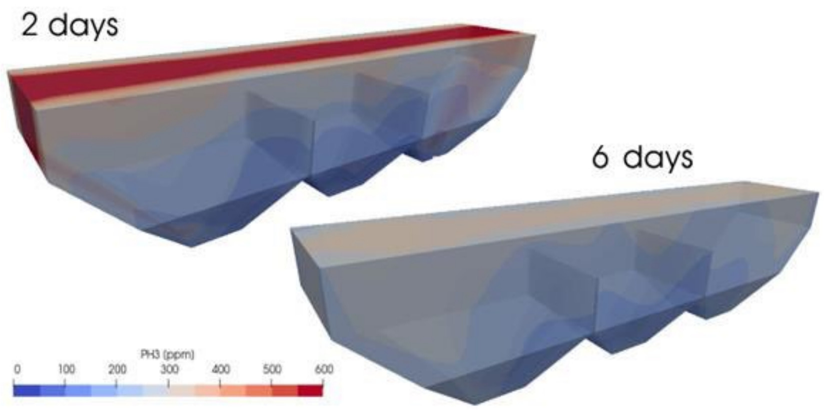

Insect Stop
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TRADE OF AGRICULTURAL PRODUCTS
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