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CONTROLLED ATMOSPHERE STORAGE RESEARCH AND TECHNOLOGY IN CANADA

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ABSTRACT

Limited work has been done in the past on modified atmospheres for the control of stored-grain pests in Canada because of the effectiveness of phosphine, methyl bromide, and the liquid fumigants, and the relatively high cost of carbon dioxide at Can.$250/t, as compared with U.S.$100/t near large production facilities in the United States. Work by E. J. Bond and colleagues in London, Ontario, focused on the effects of oxygen levels on fumigant toxicity to insects, carbon dioxide synergism with fumigants at low temperatures, and the development of resistance to carbon dioxide in the granary weevil. Fears of fumigant hazard to applicators and to consumers through chemical residues in food, and slowly increasing pest resistance to phosphine have led to our current research in Winnipeg on modified atmospheres for pest control in stored grain. Numerous laboratory and small-bin studies have defined the effects of elevated carbon dioxide (10-50%) and depleted oxygen (10-18%) on stored-grain ecosystems (seed, microflora, insects, mites) at warm and cool temperatures. Laboratory equipment has been constructed to observe the response of insects to gas gradients in grain and to determine dose-time responses for various pest species. A 3-dimensional computer model to describe CO_2 diffusion in grain is being developed and verified. The aim of current research is to develop and integrate models for CO_2 diffusion, temperature change, and moisture movement in bulk grain to predict the amount of CO_2 and length of time needed for pest control.

INTRODUCTION

Economic losses associated with insects, mites, and molds, in terms of both prevention and damage, are relatively low in Canada as compared with warmer regions of the world. We estimate total losses to range from $200-$564 million per annum throughout the grain handling and processing chain depending on harvest conditions. Although about 46 Mt of all grains harvested annually are valued at $5 billion (Canada Grains Council, 1990), only about $2 million are spent each year on fumigation for insect control (Waithe, 1990, 1991). However, Canada has a legally defined zero tolerance for insects in stored grain (Canada Grain Act, 1970). Although insect detection is usually low, at 1-3% of railcars sampled at terminal elevators, low infestation levels on farms (Madrid *et al.*, 1990), in primary elevators (Smith, 1985) or terminal elevators and flour and feed mills (Sinha and Watters, 1985), are common. The main granivorous insect pests on farms in western Canada, where most long-term storage occurs, are the rusty grain beetle, *Cryptolestes ferrugineus* (Stephens) and the red flour beetle, *Tribolium castaneum* (Herbst.); very infrequently the lesser grain borer, *Rhyzopertha dominica* (F.) and the rice weevil, *Sitophilus oryzae* (L.) are found in stored cereals on farms (Madrid *et al.*, 1990). *Oryzaephilus surinamensis* (L.) is detected less frequently today than in the past. Outbreaks of pest insects occur on an irregular basis; large numbers are related to hot harvests, as in 1991, when 120 out of 132 farmer clients at one primary elevator in Claydon, Saskatchewan, delivered grain infested with *C. ferrugineus* (Sinha and White, 1991).

Research on the use of controlled atmospheres to control insects in stored-grain has received limited attention in Canada until recently. In 1984, the liquid fumigants were de-registered in Canada because of suspected carcinogenicity to humans (Anonymous, 1984). There are currently concerns about the safety of phosphine to applicators (Garry *et al.*, 1989). Also, there are problems caused by fumigant resistance in insects (Taylor, 1989), and malathion resistance in beetles country-wide (White and Watters, 1983; White and Bell, 1990) and in the Indian meal moth, *Plodia interpunctella* (Hübner) in warmer areas of the country such as southern Ontario (Schaafsma, 1990). De-registration of phosphine and methyl bromide would result in a $20-$160 million annual loss in Canada owing to pests in stored grain, 30% of which would occur on farms, and 70% in elevators (Waithe, 1991).

The cost of carbon dioxide in Canada at about Can.$250 /t, as compared with about U.S.$100 /t near large production facilities in the United States, non-airtight farm bins, and often cool grain have made controlled atmosphere research a secondary concern. However, changing circumstances, including increased producer interest and the proven commercial effectiveness of CO_2 atmospheres to disinfest grain in railway hopper cars (Powell, 1992) and in silos at Ogilvie Mills in Montreal, Quebec, have led to increased research on controlled atmospheres. Ogilvie Mills is currently planning to build a special fumigation structure with built-in CO_2 tanks.

RESEARCH IN LONDON, ONTARIO

Bond and colleagues at the Agriculture Canada Research Centre in London, Ontario, conducted several studies on controlled atmospheres in conjunction with their research on grain fumigants. The several studies indicated the effects of oxygen levels on fumigant toxicity to insects (Bond, 1962, 1963; Bond *et al.*, 1967) and a review of these effects was published (Bond and Monro, 1967). A wide range of responses by various species of insect to O_2 levels were reported, and the mode of action of various fumigants in conjunction with limited O_2 supply was discussed (Bond and Monro, 1967).

Bond and Buckland (1978) observed the toxicity of five fumigants in the presence of CO_2 at low temperatures. They found that 20-50% CO_2 was most effective in enhancing fumigant toxicity, and that the toxicity of acrylonitrile or an acrylonitrile-methyl bromide mixture was increased more than that of methyl bromide, phosphine, or hydrogen cyanide. The effectiveness of CO_2 declined with lowering temperatures until it did not increase toxicity of the fumigants at 0°C. Kashi and Bond (1975) demonstrated that CO_2 plus phosphine resulted in more rapid kill of insects than did phosphine alone; from 4 - 64% CO_2 there was a constant 20% increase in O_2 consumption but phosphine uptake increased by up to threefold. Carbon dioxide exposure before or after phosphine exposure had no effect on mortality.

Bond and Buckland (1979) also demonstrated that resistance to CO_2 could be elicited by selection. In seven generations of *Sitophilus granarius* L., they produced a threefold increase in tolerance to CO_2.

RESEARCH IN WINNIPEG, MANITOBA

Carbon dioxide production in stored-grain ecosystems

The production of CO_2 as an incipient warning of grain deterioration was studied in non-airtight granaries and can be extrapolated to hermetic storage conditions.

White *et al.* (1982a, b) determined the rates of CO_2 production from respiration of grain and molds over wide ranges of temperature and moisture contents for wheat and rapeseed. Sinha *et al.*, (1986a, b, c) determined levels of CO_2 produced by insects in bottles or bags of wheat, and measured naturally-occurring levels of 2% or higher in infested, steel, non-airtight bins of corn, barley, and wheat.

Brief reports on the toxicity of N_2 or CO_2 to some insects and mites were reported by Barker (1979, 1980, 1981a, b). He noted that hypopi and mobile stages of the grain mite *Lepidoglyphus destructor* (Schrank) (Barker, 1981a), and eggs and adults of the rusty grain beetle, *C. ferrugineus* (Barker, 1981b) survived N_2 levels <100% and that hypopi of *L. destructor* were hard to kill with CO_2 (Barker, 1980) while adults of *C. ferrugineus* were more susceptible to CO_2 than were eggs (Barker, 1979).

Recently, our research group at the Department of Agricultural Engineering, University of Manitoba and at the Winnipeg Research Station of Agriculture Canada have initiated a research program with the long-term objective of minimizing qualitative and quantitative losses resulting from pest infestations in stored cereals, by using modified atmospheres of elevated CO_2 and depleted O_2. The specific objectives are: (i) to determine the diffusion coefficient of CO_2 through stored wheat, barley, oats, and canola as a function of seed moisture content, foreign material in the sample, temperature, kernel orientation, method of bin filling (loose and dense), and initial gas concentration gradient across the sample; (ii) to predict the distribution of CO_2 in stored-grain using a mathematical model of CO_2 diffusion through the intergranular space, including natural convection currents predicted by means of a heat transfer model; (iii) to determine the gas mixtures required to effectively control all life stages of rusty grain beetles (*C. ferrugineus*), and grain mites (*Aeroglyphus robustus* [Banks]) at various temperatures and relative humidities expected during storage of grain in Canada; (iv) to develop mathematical models of insect mortality as a function of gaseous composition, temperature, and relative humidity; and (v) to integrate models of heat transfer, insect mortality, CO_2 diffusion and adsorption, moisture diffusion and models of CO_2, moisture, and heat production by grain and insects. Such a combined model is needed to develop strategies for the cost-effective control of insect pests in stored-grains.

Farm-size bin experiments

Five farm-size bins (two 43-t capacity, three 110-t capacity) were instrumented to study the effect of elevated CO_2 on the control of insects and mites and obtain data for the validation of mathematical models of heat, moisture, and gas transfer. Each bin was instrumented to collect 30 samples of caged insects, 30 gas samples and 64 temperature readings. The monitoring of temperature at 6 h intervals and moisture content of grain at 1 wk intervals was started on September 3, 1990 and is continuing.

Mathematical modeling

Three-dimensional heat transfer models were developed and solved using the finite difference method (Alagusundaram *et al.*, 1990b) and the finite element method (Alagusundaram *et al.*, 1990a) for prediction of grain temperature as affected by weather (air temperature, solar radiation, and wind velocity) surrounding the bin, soil temperatures under the bin floor, and internal heat generation due to respiration of grain, microorganisms, and insects. The predictions of the models were accurately validated with the experimental data of Muir *et al.* (1980). The finite-element solution is capable of handling irregular boundaries and thus can be used for cylindrical, rectangular, and hopper-bottom bins and for bins with a non-leveled grain surface.

Singh *et al.* (1984, 1985) determined the diffusion coefficient of CO_2 through wheat, rapeseed, maize, and oats in different directions at different grain moisture contents. The diffusion coefficients for CO_2 in bulks of rapeseed at 8% moisture content (MC), wet basis, wheat at 13% MC, maize at 14% MC, and oats at 14.5% MC were 2.8, 3.5, 3.0, and 3.9 mm^2/s, respectively at 10°C. A mathematical model for the diffusion of CO_2 in stored wheat was developed (Singh *et al.,* 1983) and later modified (Jayas *et al.,* 1988). The model was solved for axisymmetric configurations. Because spoilage of grain can occur at any point in a grain mass and CO_2 may be introduced at one or more points non-symmetrically, there is a need to develop a three-dimensional CO_2 diffusion model. We are currently working on the solution of a diffusion model for three-dimensional configurations (Alagusundaram *et al.*, 1991b).

Grain characteristics

For modelling heat transfer in a stored bulk, two thermal properties (specific heat and thermal conductivity) for bulk grain are required. The equipment to measure thermal conductivity and specific heat of bulk grains was developed. Thermal conductivities of bulk barley, lentils and peas were measured (Alagusundaram *et al.*, 1991a). Experiments for measurement of specific heat will be conducted in the future.

Two physical properties which are needed in modelling heat transfer and diffusion of CO_2 through bulk grain are bulk density and porosity of grain. Bulk density and porosity were measured for canola (Jayas *et al.*, 1989), and other specialty seeds (Irvine *et al.*, 1991).

Seed moisture content and relative humidity of air surrounding the grain are two interrelated variables. The stored-grain is usually in equilibrium with the surrounding air. To predict the moisture content of grain using relative humidity of the surrounding air, sorption characteristics of grains are used. Sorption characteristics of flaxseed (Mazza *et al.*, 1990), sunflower, safflower, and peas were measured using a static method. These studies have resulted in the modification of the Guggenheim-Anderson-deBoer equation for incorporation of temperature effect.

Laboratory experiments

A controlled-atmospheric (CA) unit capable of generating gaseous compositions in the range of 0-100% for each of three gases (CO_2, O_2 and N_2) at any three relative humidities was fabricated (Rameshbabu *et al.*, 1990). By housing the CA unit in a temperature-controlled room, experiments can be conducted at any temperature from -20 to 40°C. The CA unit consisted of 72 cylindrical insect chambers, 50 mm in diameter and 50 mm high. Adults and eggs of rusty grain beetles, *C. ferrugineus*, the most serious pest of stored grain in Canada, were exposed to various levels of gas composition, relative humidity, and temperature in the cylindrical exposure units. Mortalities of both adults and eggs increased with increased CO_2, temperature and exposure time and decreased with increased relative humidity and O_2. Maximum mortality in 96 h for adults (99%) and eggs (85%) was obtained at high CO_2 (≈90%), low O_2 (<1%), high temperature (≈20°C) and low relative humidity (≈60%) (Rameshbabu *et al.*, 1991). White *et al.* (1988) observed the effects of CO_2 levels and temperature on adult survival and reproduction of *C. ferrugineus*, and determined that fumigation of grain for 1 wk at 20°C would require 94% CO_2 and <1% O_2. Ongoing research is underway to quantify CO_2 adsorption by various grains under various conditions.

Pilot-scale tests

Fifteen mini-bins of 444-L capacity were fabricated. The bins were 1.7-m tall and 0.6-m in diameter and were supported on concrete blocks. Six grain-sampling ports, gas-sampling ports, and thermocouples were placed in a spiral pattern along walls of the bins with one centered in the bottom of the bin. Each instrumented bin was filled with 322-kg wheat and artificially-nfested with insects that were allowed to multiply for 1 month. Different amounts of CO_2 in triplicate bins were created and bins were placed in a room at 25±3°C or at temperatures declining from 21 to 7°C (White *et al.*, 1990). Insects were controlled after 4-6 wk at 25±3°C when CO_2 levels were about 20% and O_2 levels were from 5 to 10%. At temperatures declining from 21 to 7°C, 99.6% of *C. ferrugineus* populations were killed within 12 wk, when CO_2 levels fell gradually from 20-9% and O_2 levels rose from 16-19.5%. Further tests have indicated that four CO_2 surges between 15 and 50% on weeks 0, 1, 2, and 4 in bins with 6-day half-lives for CO_2 loss virtually eliminated insect and mite pests in 42 days at 12 to 15°C (White and Jayas, 1991). The use of dry ice as a source of CO_2, rather than compressed gas, permits a more accurate application of gas (White and Jayas, 1992).

FUTURE

The on-going research on controlled atmospheres may make the use of CO_2 a commercially-viable fumigation technique, even though the costs of he gas are relatively high in Canada. The major drawback to the use of CO_2 s the lack of air-tightness in most farm granaries.

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