

Effectiveness of flameless catalytic infrared radiation against life stages of three stored-product insect species in stored wheat

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Abstract

A bench top flameless catalytic infrared emitter was evaluated in the laboratory to disinfest wheat containing different life stages (ages) of the lesser grain borer, *Rhyzopertha dominica*; rice weevil, *Sitophilus oryzae*; and red flour beetle, *Tribolium castaneum*. The emitter produces infrared in the 3 to 7 μm range. A non-contact infrared thermometer obtained real-time grain temperatures during exposures of uninfested and infested wheat containing various life stages of the three insect species. The grain temperatures attained were influenced by wheat quantity, distance from the emitter, and exposure time, which in turn influenced effectiveness against various life stages of the three species. In general, higher grain temperatures were attained in 113.5 g of wheat as opposed to 227.0 g, at 8.0 cm from the emitter surface rather than at 12.7 cm, and during a 60-sec exposure compared to a 45-sec exposure. Logistic regression indicated the probability of death of various life stages of *R. dominica*, *S. oryzae*, and *T. castaneum* was temperature-dependent. About 99 to 100% mortality of all life stages of the three species occurred when the mean wheat temperatures were in the range of 108 to 114°C. The promising results show flameless catalytic infrared technology to be a viable option for disinfestation of stored wheat, provided such high temperatures do not affect grain quality.

Keywords: Infrared radiation, Stored-product insects, Non-chemical method, Efficacy assessment

1. Introduction

Stored-product insects in grain have been traditionally managed by chemical methods (Martin et al., 1997). Reliance on chemicals has led to several stored-product insects developing resistance to traditionally used pesticides (Subramanyam and Hagstrum, 1996). In addition, new government policies on chemical residues in food and consumer's demand for safer, healthier food necessitate exploring nonchemical alternatives for managing insects associated with stored commodities.

Infrared radiation technology, a nonchemical alternative, has been used to disinfest both soft wheat grain and paddy rice (Tilton and Schroeder, 1963; Cogburn et al., 1971; Kirkpatrick et al., 1972; Kirkpatrick, 1975; Tilton et al., 1983). A 40-sec exposure resulted in 99.6% mortality of adults of 12 stored-product insects in wheat (Kirkpatrick et al., 1972). The infrared generators used in these evaluations had an open flame with temperatures >926°C (Kirkpatrick and Cagle, 1978). Such high temperatures and open flames are not suitable for use in grain-handling facilities because of explosion hazards. In addition, in previous studies, grain temperatures were measured after exposure to infrared radiation, which resulted in underestimating actual temperatures attained by the grain. Flameless catalytic infrared radiation is a new and green technology developed by Catalytic Drying Technologies, LLC., in Independence, KS, USA. (www.catalyticdrying.com). The flameless infrared radiation is emitted when propane combusts in presence of a platinum catalyst generating temperatures around 400°C (Gabel et al., 2006; Pan et al., 2008). The 3 to 7 μm infrared energy is readily absorbed by water molecules, resulting in increased temperatures. Since stored-product insects have higher moisture content (~60%) than grain (11-13%), the former will receive a lethal dose of infrared energy. This green technology may be a viable alternative to traditionally used grain protectants and the fumigant phosphine. The objectives of this research were to examine factors influencing effectiveness of flameless catalytic infrared energy against various life stages (ages) of three economically important insect species associated with stored wheat.

2. Materials and methods

2.1. Insect rearing

The lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) and rice weevil, *Sitophilus oryzae* (L.) (Coleoptera: Curculionidae) were reared on organic whole wheat (Heartland Mills, Marienthal, KS, USA). The red flour beetle, *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae), was reared on 95% whole wheat flour plus 5% (by wt) of Brewer's yeast diet. All cultures were reared at 28°C, 65% r.h., and 14:10 (L:D) h photoperiod in laboratory growth chambers.

2.2. Grain infestation and infrared treatment

Three factors that influence infrared radiation intensity, grain quantity (113.5 and 227.0 g), distance from the emitter (8.0 and 12.7 cm), and exposure time (45 and 60 s) were investigated. Only organic hard red winter wheat was used in biological tests reported in this paper. One hundred unsexed adults of *R. dominica*, or *S. oryzae* from cultures were added to each jar (113.5 or 227.0 g). After 3 d of infestation, the adults were removed by sifting the contents, and all grain contents including eggs of *R. dominica* that were laid outside of kernels were collected and placed back in the jar. The jars with 3-d-old eggs represented age 0 for the two species. Jars held in the growth chamber at 28°C and 65% r.h. for 7, 14, 21 and 24 d represented larvae in different developmental stages, and jars held for 28 d represented pupal and adults within kernels only for *R. dominica*. To expose adults of *R. dominica* to infrared radiation, 100 adults collected from culture jars were directly added to wheat. For *S. oryzae*, 7, 14, and 21 d infested samples represented larval stages while 24 d samples represented pupal stages, and 28 d sample represented adults within kernels and a few that emerged from kernels. Jars held 2 wks past 28 d had adults of *S. oryzae* and these were directly exposed to infrared radiation. The development of internal stages for both species was verified by radiographic analysis using the Faxitron X-ray device (Model 43855A; Faxitron X-Ray Corporation, Lincolnshire, IL, USA).

In the case of *T. castaneum*, 100 unsexed 2-wk-old adults from cultures were introduced into several jars each containing 100 g of flour plus yeast diet. The procedures for extracting eggs, young larvae, old larvae, pupae, and adults of *T. castaneum*, for use in tests, were similar to those described by Mahroof et al. (2003). Eggs were collected within 24 h of infestation (day 0), and larvae in various developmental stages were collected from these infested jars on days 7, 14, and 21; insects collected on day 24 presented the pupal stage. Adults (2-wk-old) needed for exposures were directly collected from the jars. For exposures, 100 individuals of all stages were used, except for the egg stage where 50 were used.

The bench top infrared emitter model, donated by Catalytic Drying Technologies LLC., has a circular heating surface of 613.36 cm², and is fueled by a 473-ml container of propane (Ozark Trail Propane Fuel, Bentonville, AR, USA) at 28.0-cm water column pressure. A steel pan of 27.94-cm diameter and 3.8-cm deep with a steel handle (43-cm long) was used to expose infested wheat in a single layer to infrared radiation. Temperature of exposed wheat was measured continuously at the center of the pan using a non-contact infrared thermometer (Raynger MX4 Model 4TP78 Raytek®, Santa Cruz, CA, USA) placed 75 cm away from the emitter. The thermometer was connected via an USB port to a laptop computer to record "real-time" grain temperatures every second (LabVIEW (National Instruments Corporation, Austin, TX, USA)).

2.3. Assessment of insect mortality

Wheat exposed to infrared radiation was placed back in jars and held at 28°C and 65% r.h. Adult mortality was determined after a 24 h holding time. Mortality of immature stages was based on number of adults that emerged from those stages. These values were compared with adult emergence in untreated wheat samples that were infested similarly.

2.4. Experimental design and data analysis

The experiment was run as a completely randomized design. The mean temperature attained every second was plotted as a function of time for 113.5 and 227.0 g of wheat exposed for 45 and 60 s at 8.0 and 12.7 cm from the infrared emitter. The temperature profile for each replicate was also averaged over time for use in logistic regression (see below).

The number of adults that emerged from untreated wheat and those exposed to infrared in the various treatment combinations was recorded. The main effect of insect age, wheat quantity, distance from

emitter, and exposure time, and their two-way interactions on the probability of death were determined using logistic regression at $P=0.05$ (SAS Institute, 2002). Odds ratios from logistic regression were used to show differences in susceptibility (odds of dying) of various life stages exposed to infrared. Differences in susceptibility of various life stages was also shown by plotting probability of death as a function of mean temperature attained averaged over wheat quantity, distance from the emitter, and exposure time.

3. Results and discussion

A comparison of temperature profiles across various ages showed that for any given quantity of grain, distance from emitter and exposure time, the profiles were essentially similar. The temperatures attained were generally greater when wheat was exposed for longer time periods at same grain quantity and distance from the emitter. Figure 1 is a representative temperature profile obtained for wheat exposed to infrared radiation in 113.5 and 227.0 g of wheat at distances of 8.0 and 12.7 cm from the emitter for 45 and 60 s. The time-dependent temperature profile was highest for 113.5 g of wheat exposed for 45 or 60 s at a distance of 8.0 cm from the emitter followed by 113.5 g of wheat exposed at 12.7 cm than in 227.0 g samples. Additional information about temperature profiles and statistical comparisons are not provided here because of space limitations, but these are explained in detail in a thesis (Khamis, 2009).

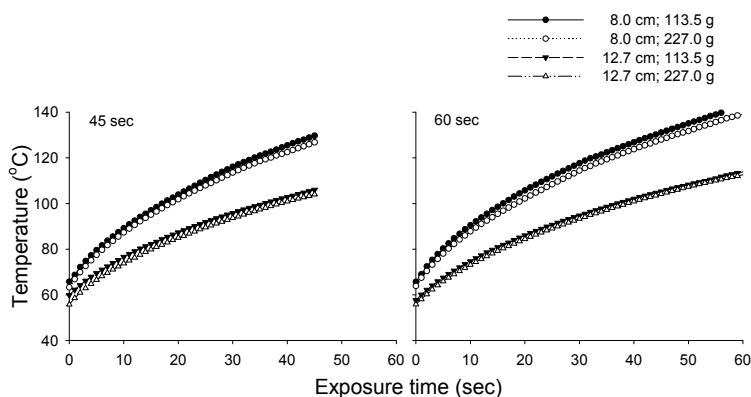


Figure 1 A generalized time-dependent temperature profile attained with different quantities of wheat exposed at 8.0 and 12.7 cm from the emitter surface for 45 or 60 sec.

The temperatures we observed were twice as high as those reported by other researchers (Tilton and Schroeder, 1963; Kirkpatrick, 1975; Kirkpatrick and Cagle, 1978; Tilton et al., 1983; Pan et al., 2008) in various stored commodities, including wheat. Unlike our tests, previous researchers measured grain temperature after infrared exposures rather than in real time.

About 212 to 581 *R. dominica* and 216 to 403 *S. oryzae* adults emerged from uninfested wheat samples. Consistently more adults of both species emerged in 227.0 g of wheat compared with 113.5 g of wheat, irrespective of insect age. It is hard to explain why more *R. dominica* adults emerged from 227.0 g than 113.5 g of wheat, besides the fact that there were twice as many kernels in 227.0 g of wheat. Toews et al. (2000) reported on adult progeny production when 100 g of each of eight United States wheat cultivars were infested with 50 unsexed *R. dominica* adults for 7 d. In their study, they carried out three separate experiments and progeny production was determined at 27 and 34°C at 70% r.h. They found large differences in progeny production, which varied from a low of 123 to a high of 940 adults. Campbell (2002) reported that *S. oryzae* laid more eggs in kernels that weighed = 20 mg. The consistently greater progeny production of *S. oryzae* in 227.0 g of wheat compared with 113.5 g could be due to the availability of more kernels that weighed = 20 mg, or it could just be natural variability in the number of eggs laid by the mixed age adults used in our study.

Logistic regression analysis showed that the probability of death of all three species was influenced significantly ($P < 0.05$) by insect age, wheat quantity, distance from the emitter, and to a lesser extent on exposure time (Table 1). Increasing the grain quantity or increasing the emitter distance resulted in lower

probability of insect death (Figures 2-4). In the case of *R. dominica*, irrespective of insect age, the best treatment appeared to be 113.5 g of wheat exposed for 60 s at a distance of 8.0 cm from the emitter, because in these treatments mean temperatures attained 108 to 114°C, and the probability of death ranged from 0.99 to 1.00 (99.0 to 100.0% mortality). Complete mortality of all insect ages of *S. oryzae* was achieved in 113.5 g of grain, exposed for 60 s, at 8.0 cm from the emitter surface resulting in grain temperatures of 108 to 112°C. The variation in probability of death of various life stages of *T. castaneum* was evident at mean grain temperatures below 105°C. Across grain quantities, exposure times, and distance from emitter, all life stages of this species were killed when the mean grain temperatures attained were between 108 and 111°C.

Table 1 Logistic regression statistics showing the influence of main and interactive effects on probability of death for three insect species exposed to infrared radiation.

Effect	<i>R. dominica</i>			<i>S. oryzae</i>		<i>T. castaneum</i>		
	df	χ^2	$P > \chi^2$	χ^2	$P > \chi^2$	df	χ^2	$P > \chi^2$
Insect age	6	642.6	<0.0001	1404.5	<0.0001	5	26.7	<0.0001
Grain quantity	1	323.1	<0.0001	18.1	<0.0001	1	67.9	<0.0001
Emitter distance	1	342.7	<0.0001	111.6	<0.0001	1	51.3	<0.0001
Exposure time	1	223.8	<0.0001	2.5	0.1111*	1	97.7	<0.0001
Age × Quantity	6	154.7	<0.0001	89.6	<0.0001	5	34.8	<0.0001
Age × Distance	6	281.5	<0.0001	144.4	<0.0001	5	18.1	<0.0001
Age × Time	6	565.6	<0.0001	182.2	<0.0001	5	44.3	<0.0001
Distance × Quantity	1	82.8	<0.0001	12.0	<0.0005	1	8.4	<0.0001
Quantity × Time	1	47.1	<0.0001	---	---	---	---	---
Distance × Time	1	84.0	<0.0001	47.1	<0.0001	1	13.3	<0.0001

*Not significant ($P > 0.05$). This is the only non-significant value. **The model could not be fit to the data.

Odds ratios showed differences in susceptibility among life stages to infrared radiation, and these susceptibility trends varied by species. For example, with *R. dominica*, the odds ratio for 21-d-old insects was 0.94 when compared with the adults (1), which were the next least susceptible stage to infrared. Odds ratios for the other stages in increasing order were eggs (1.45), 24-d-old insects (2.35), 14-d-old insects (2.41), and 7-d-old insects (3.80). With *S. oryzae*, eggs were the least susceptible stage (odds ratio, 0.02), followed by adults within kernels (28-d-old; 0.14), pupae (24-d-old, 0.18), young-to-old larvae (7- to 21-d-old; range, 0.49-0.73), and 42-d-old adults (1). Both insect mortality (probability of death data) and odds ratios for *T. castaneum* showed that pupae were the least susceptible stage (odds ratio, 0.52), followed by eggs (0.66), adults (1), old larvae (21-d-old, 1.46), mid-to-old larvae (14-d-old, 1.78), and young larvae (7-d-old, 2.86).

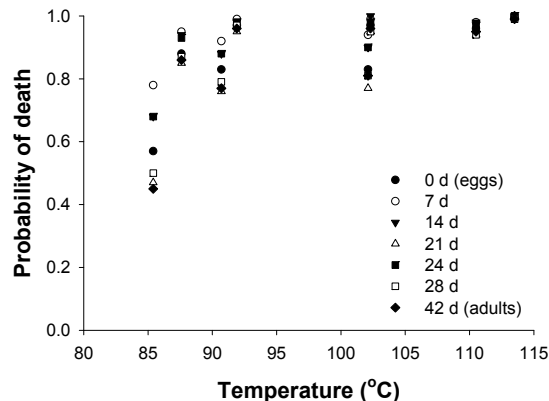


Figure 2 Probability of death of different ages of *R. dominica* as a function of mean wheat temperature.

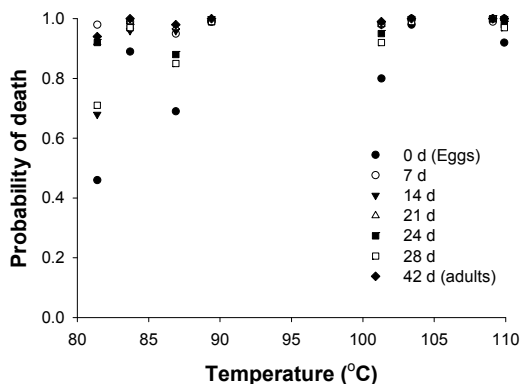


Figure 3 Probability of death of different ages of *S. oryzae* as a function of mean wheat temperature.

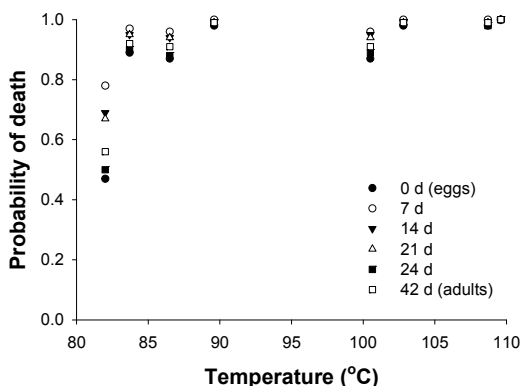


Figure 4 Probability of death of different ages of *T. castaneum* as a function of mean wheat temperature.

The variation in susceptibility among life stages and species may be related to the adverse effects of infrared on the insect's physiological processes. Except for the egg and adult stages, all other stages of *R. dominica* and all life stages of *S. oryzae* are spent within kernels. The location of the insect within the kernel may also influence its susceptibility to heat. In the case of adults of all species and larvae of *T. castaneum*, their ability to move away from areas that are hotter to seek cooler areas may make them less susceptible to heat. We found eggs to be relatively more tolerant to infrared radiation. Kirkpatrick (1975) reported only 8% percent mortality of eggs and first instars when exposed to infrared radiation. Some of the eggs could have escaped infrared treatment, perhaps by being shielded by kernels.

In summary, to completely control all life stages of the three species, the best infrared treatment appeared to be 113.5 g of wheat exposed for 60 s at a distance of 8.0 cm from the emitter; in these treatments mean temperatures attained 108 to 114°C. These results show that flameless catalytic infrared radiation technology may be valuable tool for disinfecting stored grain. Quality tests with infrared treatments reported here revealed no adverse effects on the physical, chemical rheological, and end-use qualities of wheat (Khamis, 2009).

- ❖ Mention of trade or proprietary names in this publication does not imply an endorsement by Kansas State University or the USDA.

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