COMBINATIONS OF PARTIAL VACUUM WITH MICROWAVE OR INFRARED HEATING OF GRAIN FOR INSECT CONTROL[1,2]

by
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Abstract

Stored-product insect infestations in grain were controlled in laboratory tests by a combination of microwave heating and partial vacuum. As with other methods of controlling insects with heat, the rate of heating (i.e., intensity of microwave energy) appeared to be very important.

In a follow-up study, a pilot-scale microwave/vacuum grain dryer was tested. The lesser grain borer, Rhyzopertha dominica (Fabricius), and the rice weevil, Sitophilus oryzae (Linnaeus), infesting wheat were killed by application of 1.0 power density unit of microwaves at 2.45 GHz while under 35 torr (35mm Hg. vacuum). Lower intensities of microwaves at this pressure did not produce complete control of the insects.

Laboratory studies of combining infrared heating with 25 torr pressure (IR/vac) showed that IR/vac was significantly more effective than IR without vacuum in controlling two species of stored-grain insects.

This report summarizes recent work reported by the authors.

Introduction

High temperatures have been used to control stored-product insects for many years (Oosthuizen 1935, Dean 1937). With the advent of chemical control methods, this method became far less prevalent than

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[1]Mention of a commercial or proprietary product does not constitute an endorsement of this product by the USDA.

[2]The term power density unit (PDU) has been used throughout this report to indicate relative power densities. This has been done to protect the proprietary interests of McDonnell Aircraft Co. until patent applications have been processed.

before; however, the disinfesting procedures now in use, i.e., fumigation or residual insecticide treatments, require that grain remain undisturbed for several days before shipment, leave undesirable residues on the grain, or both. Many means of control have been tested to eliminate these problem areas. Much recent work has been done with methods for rapid heating of grain for insect control. Methods explored include heated fluidized beds (Dermott and Evans, 1978, Vardell and Tilton, 1981a,b), microwave, dielectric and infrared heating as a means of disinfestation (Boulanger et al 1971, Kirkpatrick et al 1972, Kirkpatrick and Tilton 1972, Nelson 1973, and Watters 1976).

Microwave heating of grain appears especially promising because of the rapid, uniform heating of grain in a grain stream and because it can be easily adapted for use with industrial grain moving equipment. Also, there are possibilities of effects of microwaves on insects other than strictly thermal. However, Kirkpartick et al. (1972) compared the effectiveness of microwave to infrared heating, another of the rapid methods of heating grain. They reported that when grain was heated to 57 C (measured as grain surface and intersitial air space temperature), infrared heating produced a greater percentage of mortality of internal preadult rice weevils, Sitophilus oryzae (Linnaeus), infesting soft winter wheat than did microwave heating when comparable temperatures were used. Kirkpatrick (1974), in a review paper stated that most internal-feeding insects that infest stored grain can be controlled with temperatures of 65 C produced by microwaves, and those exposures do not damage wheat germination if moisture content remains below 14%. Cowpea weevils, Callosobruchus maculatus (Fabricius), infesting black-eyed peas was an exception. Both larvae and pupae survived a peak temperature of 76.7 C but germination is reduced 42% at this temperature. There may be other exceptions to be found in Callosobruchus spp. on other leguminous seeds. This report summarizes recent work reported by the authors.

Microwave Heating Under Vacuum

A crop drying system has been developed by the McDonnell-Douglas Corp., St. Louis, MO, whereby a moving stream of grain under partial vacuum is subjected to microwave energy (Forwalter 1978). Water loss, both in the grain and infesting insects, was greatly increased under partial vacuum. The drying effect of microwave heating on the grain and infesting insects was thereby, greatly increased. Also, other effects of microwaves on insects may be increased under reduced pressure, two important factors being the reduced boiling points of water and hemolymph and the reduced protein coagulation point.

Preliminary cooperative tests conducted in their St. Louis facility and at our laboratory in Savannah, Georgia, showed that this technique could be adapted for stored-product insect control (Tilton and Vardell 1982a). In those early tests it was shown that the effects of heating

insects to temperatures of ca. 40-45 C under partial vacuum of 35 torr (35mm Hg.) may be quite severe. It was also shown that the rate of heating (i.e., the microwave intensity) is extremely important. In the first preliminary tests all immature stages of Angoumois grain moth, Sitotroga cerealella (Oliver), lesser grain borer, R. dominica , rice weevil, S. oryzae, maize weevil, Sitophilus zeamais Motschulsky, within kernels of wheat, rye or corn (maize) were treated. Treatments consisted of three intensities of microwaves with all three having the same total energy input and all were subjected to a 35 torr vacuum during treatment. The effects of rate of heating is clearly shown in table 1.

Table 1 - Mean numbers of Angoumois grain moth adults emerging from five replicates[1]/ of rye, corn, or wheat treated with microwaves and vacuum.

Power Density Unit	Time (min)	Pressure (torr)	Grain[2]/		
			Rye	Corn	Wheat
0.00	0	760	15.00a	20.20a	193.00a
0.03	90	35	11.80a	14.20b	166.80a
0.08	30	35	3.00b	6.25c	108.00b
0.28	10	35	0.00c	0.00d	3.20c

[1]Only four replicates were used in the 0.08 PDU treatment.
[2]Means in each column followed by the same letter are not significantly different according to Duncan's multiple range test at the 0.05 level of significance.

With the equipment available it was impossible to monitor temperatures during treatment; however, in a second test temperatures immediately after treatment were recorded. As would be expected microwave-treated grain samples subjected to vacuum did not reach the same high temperatures as samples that were treated at atmospheric temperatures (Table 2). In this test, one series of treatments were subjected to 35 torr only and there was no significant difference between this treatment and the controls. All of the treatments, in which microwaves were used, resulted in significantly fewer emerging adults than did the atmospheric or vacuum controls. Only when the high dosage of microwaves (0.38 PDU) was combined with low pressure (35 torr) was complete control of the infestations achieved.

Table 2 - Mean numbers of adult rice weevils (RW) and lesser grain borers (LGB) emerging from five replicates of infested wheat and rye treated with different combinations and levels of microwaves and vacuum.[1]

Treatment	PDU[2]	Pressure (torr)	Post-treatment temp(C)	Emergence			
				Wheat		Rye	
				RW	LGB	RW	LGB
ATMOS - CK	0.00	760	25.6	6.4a	13.4a	46.8a	168.6a
Vacuum - CK	0.00	35	26.7	5.8a	4.6b	51.4a	178.8a
Low - ATMOS	.34	760	55.6	2.6b	1.4c	0.4b	6.0c
High - ATMOS	.38	760	60.0	0.8c	0.6d	1.2b	8.4c
Low - VAC	.34	35	43.3	0.2c	2.2c	2.6b	76.6b
High - VAC	.38	35	41.1	0.0d	0.0e	0.0c	0.0d

[1]Means in each column followed by a different letter are significantly different as determined by Duncan's multiple range test at the 0.05 level of significance.
[2]"PDU" denotes power density units - see footnote 2 of the text.

Following these tests we then conducted tests in cooperation with McDonnell-Douglas Corp. and the Harvesting and Processing Research Unit, USDA, SEA/AR, Tifton, Georgia. All treatments were made using the pilot scale microwave/vacuum grain dryer (MIVAC(R)) described by Forwalter (1978) and developed jointly by the Aeroglide Corp., U.S. Department of Energy, McDonnell-Douglas Corp. and the U.S. Department of Agriculture located at the University of Georgia Coastal Plain Experiment Station in Tifton, Georgia. All treatments except the untreated control were made at a pressure of 35 torr. The microwaves were generated by two 6-kw magnetrons (2,450 megahertz) which were fed into the dryer cavity via wave guides and distributed uniformly through the grain column. The experiments were conducted in two parts; in the first part the treatments were (1) controls that were passed through the unit under partial vacuum (2) partial vacuum + 0.71 PDU, (3) partial vacuum + 0.83 PDU, and (4) untreated control. In the second part the treatments were (1) controls that were passed through the unit under partial vacuum, (2) partial vacuum + 0.96, and (3) partial vacuum + 1.0 PDU, and (4) untreated control.

Before treatment, ca. 2 tons of hard red spring wheat were placed in a controlled temperature cabinet maintained at 27±1 C and 60±2% RH and infested with lesser grain borers and rice weevils. Additional insects of both species were added to the grain at ca. weekly intervals for 6 weeks to ensure that all stages would be present at the time of treatment. The week before treatment, the wheat was removed from the cabinet and mixed to ensure a uniform distribution of the infestation. The grain was then resacked for transportation to Tifton, Georgia by truck.

For treatment wheat was placed in a hopper on the top of the treatment tower. The system was closed, evacuated to treatment level, and then the magnetrons and grain feeder were started. The grain passed through a 10.16 cm diameter column. The total dosage of microwaves applied to the grain was varied by varying the magnetron output. After the grain transited the filled system, five 1.9-liter samples were taken from the sampling port located at the lower end of the grain stream. This sampling port was equipped with an airlock and was located below the metering valve at the bottom of the treatment column and allowed for sampling without interrupting the drying process. After sampling, the system was shut down, and the treatment column emptied. This procedure was repeated for each treatment including the controls that were passed through the unit under partial vacuum. The whole process was replicated three times. Untreated control samples were taken from the sacks before the wheat was placed in the treatment column. After collection, the samples were placed in 1.9-liter jars and covered with filter paper and screen wire lids and returned to the laboratory in Savannah. Upon arrival, the adults were sieved from the grain using A.S.T.M. standard screens of an appropriate size for each species and then the samples were placed in a room maintained at 27±1 C and 60% RH. Emerging adults were sieved from the samples and counted three times a week for 5 weeks.

The numbers of emerged adults from the five samples from each replicate and treatment were averaged. The mean emergence from each replicate was analyzed by use of Duncan's multiple range test at the 0.05 level of significance.

In general, the numbers of emerging adult lesser grain borers and rice weevils decreased with each increase in microwave intensity (Table 3).

Table 3 - Mean[1] numbers of lesser grain borer and rice weevil adults emerging from wheat treated with various combinations of microwaves and partial vacuum[2].

Treatment	Lesser Grain Borer		Rice Weevil
		Test I	
Atmos-Ck	438.8a[3]		172.5a
Vacuum-Ck	472.5a		210.2a
0.71 PDU[4] + Vacuum	28.8b		2.8b
0.83 PDU[4] + Vacuum	10.7c		0.7b
		Test II	
Atmos-Ck	2088.1a		1402.3a
Vacuum-Ck	502.2b		325.2b
0.96 PDU[4] + Vacuum	10.3c		4.5c
1.00 PDU[4] + Vacuum	0.0d		0.0d

[1]The numbers given are the mean emergence from five 1.9-liter samples.
[2]All treatments except the untreated controls (Atmos-Ck) were made at 35 torr.
[3]Means in a column followed by a different letter are significantly different as determined by Duncan's Multiple Range Test at the 0.05 level of significance.
[4]"PDU" denotes power density units - see footnote 2 of the text.

Emergence during the first week post-exposure was completely prevented by the microwave/vacuum treatment of 0.83 PDU + partial vacuum. In the subsequent post-exposure period, only the highest exposure level (1.0 PDU) produced complete control.

In general, the percentage rice weevil emergence from all treatments involving the use of microwaves was lower than those of the lesser grain borer. Rice weevil emergence data for the first 4 weeks post exposure showed that only the highest level (1.0 PDU + vacuum) of treatment gave total control. Data from lower level treatments showed a lesser degree of control. During the fifth week post-exposure, there was no emergence from the three highest treatments.

The post-treatment grain temperatures were recorded during the sampling of the wheat by means of a thermocouple positioned into the grain stream just above the lower grain metering valve. Moisture content of the wheat was determined on the untreated wheat and at all treatment levels with a Motomco(R), Model 919, moisture meter.

The grain temperatures and moisture contents of the wheat, before and after treatment, are given in Table 4. As would be expected, the grain moisture content decreased as the final grain temperature increased. The grain temperatures after treatment increased with each increase of microwave power density applied to the wheat.

Table 4 - Wheat temperatures and moisture content before and after treatment with microwaves and partial vacuum[1].

Treatment	Temperature (C)			Moisture Content (%)		
	Before	After	Change	Before	After	Change
			TEST I			
Atmos-Ck	10.6	10.6	0	10.68	10.68	0
Vacuum-Ck	12.7	14.0	1.3	10.68	10.60	-0.08
0.71 PDU	14.8	53.8	39.0	10.68	9.63	-1.05
0.83 PDU	10.6	50.7	40.1	10.68	9.12	-1.56
			TEST II			
Atmos-Ck	17.6	16.7	-0.9	10.68	11.05	+0.37
Vacuum-Ck	16.7	20.6	3.9	11.05	10.96	-0.09
0.96 PDU[2]/	18.3	59.7	41.1	11.05	8.94	-2.11
1.00 PDU[2]/	18.3	61.8	43.5	11.05	8.77	-2.28

[1]All treatments except the untreated controls (Atmos-Ck) were made at 35 torr.
[2]"PDU" denotes power density units - see footnote 2 of the text.

Infrared Heating Under Vacuum

Another method of rapidly heating grain that may be adaptable for use under partial vacuum for grain drying or insect control is infrared radiation. A preliminary test to explore the potential of such a combination for insect control was conducted. In this test we compared treatments consisting of a combination of infrared plus 25 torr vacuum (IR/vac) and IR without vacuum. The test insects were the lesser grain borer, *R. dominica* and the rice weevil, *S. oryzae*. Different aged cultures of a species were mixed to obtain a treatment culture which contained all life stages. Each species was tested separately.

The treatment chamber was a vacuum oven modified to contain a 500 W Calrod(R) heating source positioned 6.25 cm above a pair of remotely controlled drop doors. For treatment, ca. 25 g of infested wheat was placed as a single layer on the drop doors. When vacuum was required the oven was evacuated to ca. 25 torr (25 mm. Hg.). When the vacuum had reached the desired level, the heating element was turned on to bring the grain to 52, 54 or 56 C. At the end of the heating cycle, the grain was dropped through the doors into a trough away from the influence of the heating element. Grain temperature was measured by a YSI(R) Model 47 telethermometer when the grain was in the trough. The pressure was then returned to ambient and the grain sample was removed. Evacuation time was ca. 6-1/2 min and pressure restoration time was ca. 1-1/2 min.

Treatment with 25 torr vacuum (vac) was accomplished by placing the infested wheat as a single layer in a shallow tray in the rear of the chamber and out of the range of the heating element. These treatments were made during the treatment of the lowest temperature IR/vac combination. The IR treatments were made at ambient pressure in the same manner as the IR/vac treatments. All treatments were replicated five times with five samples per replicate.

The heating time for each sample was varied individually to provide the desired grain temperature ±1 C. Heating times varied from 30 to 45 sec for the IR treatment and from 1 min to 1-1/2 min for the IR/vac treatment. The extra time for the IR/vac treatments was due to the time needed to reduce the pressure. Moisture loss was determined to the nearest 0.01 mg by weighing three of the five samples for each treatment before and after treatment. One replication was treated per day over a 10-day period. Each sample for each treatment and replicate was handled separately.

Emerging adults were sieved from the treated wheat at weekly intervals for 6 wk. Data for each species were analyzed separately using Duncan's Multiple Range Test at the 0.05 level of significance. The emergence data were then converted into percent of their individual controls for presentation in tabular form.

The vacuum treatments alone did not cause a significant change in the number of emerging adults of either species. The IR treatments showed significant reductions in the numbers of emerging adults at each treatment temperature (Table 5). The numbers of adults emerging after treatment at the two highest temperatures (54 and 56 C) were not significantly different. The IR/vacuum treatments resulted in significantly fewer emerging adults than did the single treatments. None of the treatments used in this test produced 100% mortality of the test insects.

Table 5 - Adults emerging from infested wheat treated with 25 torr vacuum (vac), infrared (IR), and IR/vac combinations; means[1]/ are expressed as percent of controls.

Treatment	Temperature (C)			Temperature (C)		
	52	54	56	52	54	56
	Lesser Grain Borer			Rice Weevil		
Vac	93.6a[2]	-	-	96.9a	-	-
IR	71.4b	45.0c	33.1d	33.4b	20.4c	20.8c
IR/Vac	38.3cd	23.9e	21.8e	14.0d	10.9d	5.2e

[1]Each value is the mean of five samples of five replicates.
[2]Means in each column followed by a different letter are significantly different as determined by Duncan's Multiple Range Test at the 0.05 level of significance.

Moisture content as determined by a Montomco Moisture Meter before treatment averaged ca. 11.85. In every case, the moisture content of the wheat was lower after treatment than in the controls (Table 6). However, in no instance was the moisture loss greater than two percent. The combination treatment of IR/vac produced the greatest moisture loss which ranged from 1.1 percent at 52 C for the rice weevil to 1.7 percent for the lesser grain borer at 56 C.

Table 6 - Percent moisture loss (wet weight basis) of infested wheat during treatment with 25 torr (vac), infrared (IR), and IR/vac combinations.

Treatment	Treatment Temp.(C)	Moisture Content Loss (%)	
		Rice Weevil	Lesser Grain Borer
Control	-	0.1	0.1
Vac	-	0.5	0.6
IR/Vac	52	1.1	1.4
	54	1.1	1.4
	56	1.4	1.7
IR	52	0.4	0.6
	54	0.5	0.6
	56	0.5	0.6

The combination treatment using IR/vac was more effective than IR alone and, with the vacuum technology presently available, a combination treatment should be feasible in a continuous flow system. Further research, on an expanded scale, should be conducted to explore the practical value of the combination treatment.

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