A Heating Block System for Studying Thermal Death Kinetics of Insect Pests

J. N. Ikediala, J. Tang, T. Wig

Abstract. *A novel heating block system to provide rates of temperature increase between 0.2 and 28°C/min was developed for investigating thermal death kinetics of insect pests. The finite element method was used to analyze heat transfer through the block system and during the heating of fifth-instar codling moths (*Cydia pomonella *L.). Measured heating rates of the block agreed with finite element predictions, and the maximum temperature difference in the testing zone was < 0.2°C at the most rapid heating of 28°C/min. Simulated temperature in the codling moth larva during 20°C/min heating to 50°C lagged behind the block temperature by a maximum of 4.6°C in the testing zone. This lag was reduced to less than 0.6°C after 30 s of holding. The temperature differential decreased with decreasing heating rate and insect size. Experiments were conducted to determine the thermal kinetics of the fifth instar codling moth at temperatures between 48 and 52°C after heating by this block system at 20°C/min. Activation energy for thermal destruction of the larvae was determined to be 499 kJ/mol, a much higher value than that for loss of fruit quality (~100 kJ/mol) due to heat treatment. The heating system can potentially be used as an effective tool to experimentally establish thermal kinetics and thermal-death-time curves for different insect pests. These values can then be used to develop appropriate quarantine treatment protocols for heat-based pest control.*

Keywords. *Quarantine treatment, Heating system, Heating rate, Finite element, Kinetics, Activation energy, Insect pests, Codling moth, Thermal death time.*

In recent years, there has been increased interest in developing thermal processes to replace chemical fumigation as quarantine and phytosanitary treatments for preshipment and export commodities, primarily due to the imminent loss of methyl bromide (Federal Clean Air Act, 1990) and increasing public concerns over chemical residues on foods. Methyl bromide (MeBr) is a relatively inexpensive and effective fumigant and has traditionally been used to control many insect pests, including quarantine insects such as the codling moth (CM). MeBr, however, has been associated with ozone depletion. The U.S. Environmental Protection Agency, under the Montreal Protocol (UNEP, 1995), has mandated a sharp reduction of MeBr use between 1999 and 2005 and cessation of its production and importation by 2005 (Federal Clean Air Act, 1990). This will likely force the United States multi-billion dollar fruit and nut industry to abandon the fumigant for the postharvest control of pests. Thus, alternative control processes need to be developed to replace current treatment practices for both the domestic and international markets.

Reports by many researchers have shown that different thermal treatment methods alone, or combined with cold storage or a controlled atmosphere, can control insect pests in selected host commodities (Sokhansanj et al., 1990, 1992; Yokoyama et al., 1991; Neven and Rehfield, 1995; Neven et al., 1996; Ikediala et al., 1999a). The USDA Animal and Plant Health Inspection Service (APHIS) has also approved several heat treatments, such as vapor heat, high-temperature forced-air, hot water dips and dry-hot air, for controlling insect pests in tropical fruits like papayas, mangoes, and banana roots (Hansen, 1992).

Critical to the development of successful alternative thermal quarantine treatments is the understanding of the delicate balance between minimal thermal impacts on commodity quality and complete kill of infesting insects. A review of literature revealed that relevant fundamental information on the thermal tolerance of both pests and commodities was lacking. When this information becomes available, new treatment protocols can be developed to deliver lethal energy doses to targeted insects while retaining product quality.

Insect pests and their host agricultural commodities differ greatly in shape and size, and in tolerance to heat and cold treatments. Much of the research on application of heat treatment to obtain quarantine security has not been systematic, and many heat treatment methods have been investigated through what can be described as trial-and-error approaches. Values of temperature ranging from 38 to 54.4°C, treatment times of up to 12 h, and heating rates between 0.067 and 6.25°C/min have all been reported (Sharp and Chew, 1987; Yokoyama et al., 1991; Neven and Rehfield, 1995; Neven, 1998a). There seems to be a lack of a consistent method to obtain experimental data that truly reflects the intrinsic heat resistance of an insect. It is often unclear if heat treatment times reported in the literature include the initial heat-up period, or how the heating rates

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effect insect mortality. In most mortality tests, heat transfer phenomena often confounded with kinetics information associated with insect mortality. In certain cases, an instantaneous heating method, such as direct hot water dip of insects, was practiced (Sharp and Chew, 1987; Jang, 1991). The probable drowning of insects at elevated temperatures in those studies may also result in misleading conclusions.

A common method for determining the thermal resistance of insects is to heat the infested commodities to selected temperatures for predetermined lengths of time, using different heat application methods (Neven and Rehfield, 1995; Neven and Mitcham, 1996; Ikediala et al., 1999a). However, it is difficult to extract the true information for the thermal resistance of insects from the experimental data because this information is confounded by the heat application method. Heating rate is believed to significantly affect insect thermal mortality because of the influence of a rapid temperature rise on insect metabolism and physiological adjustment (Evans, 1986; Stephens et al., 1994; Neven, 1998a,b). Neven (1998a) reported that lower heating rates required longer exposure times in order to achieve the same insect larvae mortality. However, a method to precisely investigate the effects of different heating rates is lacking. Furthermore, there is little information on CM heat resistance for short time heat treatment (< 3 min), at higher temperatures (> 48°C), and at heating rates between 5 and 20°C/min suitable for a fast, continuous heat treatment method.

The objectives of this study were to (1) develop and test a heating block system suitable for studying thermal effects on insect pests, and (2) use this system to investigate the thermal death kinetics of fifth-instar CM between 48 and 52°C at 20°C/min heating rate.

Materials and Methods

Insects are sensitive to heat above 42°C (Neven and Mitcham, 1996). In thermal treatments, the temperature of insect-infested commodities normally are raised to a desired temperature and held for a certain period of time to provide adequate heat lethality to kill the pest. It was our intention to develop a block system to heat insects in a confined region at controlled temperature ramping rates in order to study the thermal resistance of insect pests at temperatures above 42°C. In designing this system, it was important to choose materials with low thermal capacity and high conductivity to provide uniform temperature field in the heating region, and to enable reasonably precise control of heating rate and holding temperature. The ability to provide uniform heating was essential to ensure that all insects were exposed to the same heat treatment. The treatment system also needed to be flexible to accommodate insects of different sizes as well as the range of heating rates suitable for conventional (low heating rates) and microwave (high heating rates) heat application methods. Numerical analysis for the heat transfer was conducted to investigate the suitability of the system in providing desired heating rates and precision of temperature control. Effect of heating rate on temperature profiles, uniformity in critical parts of the heating block system, and the thermal lag in the insects were also studied. Simulation results were compared with experimental data. Finally, the results from a case study was presented to demonstrate the use of the experimental heating system to establish useful kinetics information for the pest, CM larva.

The Heating Block System

The heating block system consisted of aluminum heating blocks, a sandwiching plate, heating pads, an insulation box, and a data acquisition/control unit. Figure 1 shows a schematic diagram of the assembly. The top and bottom heating blocks, 127 × 127 × 12.7 mm, and the sandwiching plate, 127 × 127 × (1 to 3) mm were made of pure aluminum, chosen for its low thermal capacitance and high conductivity. Similar material was used by Sokhansanj et al. (1992) for insect holding container (ϕ10 × 15 cm) heated by a convection oven, when studying thermal kill of wheat midge cocoons and Hessian fly puparia. Four 25.4 × 25.4 mm holes were located symmetrically near the center of the sandwich plate. The four holes of the sandwich plate and the top and bottom blocks form holding chambers for insects. Each chamber was capable of holding a minimum of eight insects, for a total of 8 × 4 (32) or more insects, depending on the type and size of the larval stage. The thickness of the sandwich plate and size of the insect chambers can be chosen based on the sample insect length and width. Two custom-made heating pads, each rated at 250 W, were glued to the blocks using a heat-resistant adhesive. These pads were connected to ac power supply (120 V, 60 Hz) via a solid state relay. Two, precalibrated, type T thermocouples (gage 30) were used to monitor temperature. These thermocouples were placed at the geometric center of the heating block assembly and in the center of one insect chamber (fig. 1). The heating block assembly was encased in an insulation box.

A computer program was written using the visual software WorkBench PC 2.0 (Strawberry Tree Inc., Sunnyvale, Calif.) to control, acquire, display, and save real-time data during heating experiments. Different heating rates, ranging from 0.2 to 28°C/min, and control of holding temperature were achieved through the data acquisition and control system by setting selected numbers of heating pulses in microsecond time intervals. At the end of a heat treatment (ramp up + hold time), the power was switched off. The top of the insulation box and top heating block were removed, and the bottom block was overturned to remove the insects as quickly as possible.

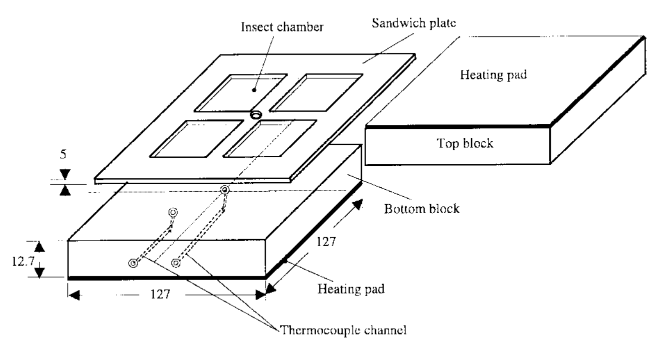


Figure 1–A schematic diagram of the heating block assembly. All dimensions are in mm.

Finite Element Model and Simulation

Heat Transfer Model. The heating block was modeled as a three-component system consisting of aluminum, air, and insects. Heat transfer through the system was assumed to be two dimensional. Thermal properties for the aluminum block, air in the insect chamber, and the insect were assumed constant in the tested temperature range between 20 and 55°C. Heat transfer resistances between the aluminum heating blocks and the sandwich plate, between the insect and the heating block, and between the insects and the air medium in the insect chamber were assumed to be negligible. Since the air gap in the insect chamber was no more than 3 mm, no convection in the air gap was assumed. Insects were also assumed to be stationary during heat treatments and made more than a point contact with the bottom block. Because of symmetry of the heating block system, the FEM analyses were conducted for one quadrant of the block as shown in figure 2.

Transient heat transfer through the block, air, and insect was governed by the following differential equation for two-dimensional heat conduction in an isotropic and composite material:

$$\rho C_p \frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (1)$$

where ρ is the mass density of the material in kg/m^3, C_p is the specific heat capacity in J/kg °C, k is the thermal conductivity in W/m °C, T is the temperature in °C, t is the time in s, and x,y is the Cartesian coordinate position in m. Equation 1 was subject to the initial condition:

$$T(x,y,t=0) = T_o(x,y) \quad (2)$$

where T_o is the initial temperature of the materials. Heat flux q, from the heating pad, in the direction normal to the interfaces between the top and bottom block and the heating pads is described by the following:

$$-k\frac{\partial T}{\partial n} = q \quad (3)$$

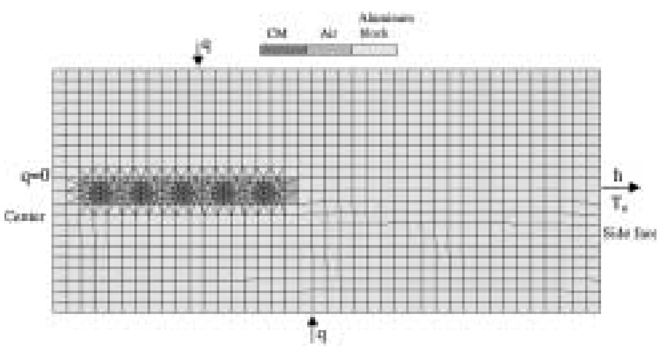


Figure 2–Discretization of one quadrant of the heating block with five codling moth (CM) larvae (represented with hexagon cross-section in the insect chamber) for finite element analysis.

where n is the outward normal direction to surface. Convective heat transfer at the block edge normal to the side was given by (fig. 2):

$$-k\frac{\partial T}{\partial n} = h\left(T - T_a\right) \quad (4)$$

where h is the surface heat transfer coefficient in W/m^2 °C, and T_a is the ambient air temperature. Heat flux at the symmetry axis of the heating blocks was:

$$q = -k\frac{\partial T}{\partial n} = 0 \quad (5)$$

The governing equation with boundary conditions was transformed into FEM matrices by the weighted residual approach based on the Galerkin approximation:

$$[M]\dot{T} + [K]T - \{F\} = 0 \quad (6)$$

where M is the capacitance matrix, K is the conductivity matrix, F is the prescribed load vector, and $\dot{T}$ is the time derivative of temperature.

Finite Element Solution and Computer Simulation. Material properties for aluminum and air were obtained from the literature (Incropera and DeWitt, 1996). Since no information was available in the literature for the thermal properties of CM larva, those values were approximated by assuming the parallel model recommended by Rahman (1995) for fresh seafoods, where the effective property (P) is predicted as a weighted arithmetic mean of the properties of the component (Choi and Okos, 1986) as:

$$P = \sum_{i=1}^{n} p_i X_i \quad (7)$$

where p_i is the property value of the i*th* major component, and X_i is the mass fraction of those components. Ikediala et al. (1999b) reported the moisture content of CM larva to be 73% w.b., while Hansen and Harwood (1968) reported 65 to 68% w.b. and a 33 to 48% dry weight of fat. Assuming the composition of larva to be 70% water, 14% fat, 6% protein and the remainder carbohydrate and ash, the values for k, ρ, and C_p for CM were estimated using equation 7, and are shown in table 1.

A CM larva cross-section was represented by a hexagon to provide for reasonable contact with the bottom heating block (fig. 2). The fifth-instars (largest larval stage) are 12

Table 1. Heat transfer parameters used in the FEM simulation

Material	Density ρ (kg/m^3)	Thermal Conductivity, k (W/m °C)	Specific Heat C_p (J/kg °C)	No. of Elements
Aluminum block/plate	2,702	234	903	853-918
Air	1.160	0.027	1,007	37-129
Codling moth larva	1030	0.510	3450	18-90
Rated power of each heating pad		250 W		
Heat flux (maximum), q		15500 W/m^2		
Heat transfer coefficient, h		5 W/m^2 °C		
Initial condition, T_o		20°C		
Environmental temperature, T_a		20°C		

to 20 mm long (Beers et al., 1993; Metcalf and Metcalf, 1993). Diapause and nondiapause fifth-instar widths at the thorax and abdomen were carefully measured with calipers before and after insects were quickly frozen at –30°C. The average width of a larva was 2.35 mm (ranged from 2.0 to 2.5 mm). Thus, a characteristic diameter of 2.5 mm was chosen for the simulation. Heat transfer analysis was conducted with conservative parameters for the CM.

A commercial finite element (FEM) software package, MARC® v7.1, running under Mentat v3.1 (MARC Analysis Research Corporation, Palo Alto, Calif.), was used to solve the system of equations 6. Three- and four-node quadratic linear elements (fig. 2), with full integration and lumped mass (heat capacity) matrix, were employed for the domain discretization and solution. The backward difference scheme was used to discretize time for transient analyses and to approximate the time derivative. Mesh refinement and time step size were varied to test the convergence of numerical results and to select optimum simulation time step and grid size. The chosen number of elements for aluminum, air and CM discretization ranged from 853 to 918, 37 to 129 and 18 (for one larva), respectively, the total number of nodes ranged from 968 to 1105, while the time step size was 1 s. Figure 2 shows the discretization in one quadrant of the heating block assembly with five CM larvae. The parameters used for the FEM simulation are shown in table 1.

A Case Study with CM Larva

Codling moth larvae were reared by the method of Toba and Howell (1991). The fifth instars are the most heat resistant growth stage (Yokoyama et al., 1991), and therefore, were used for the heat treatments. Test larvae were extracted from the diet just before each treatment, and the insects were carefully placed in the compartments of the heating block by using soft tweezers. For each run, between 18 and 30 insects (total) were distributed in the four chambers. The block temperature was then raised at 20°C/min and held at the preset temperatures of 48, 50 or 52°C for selected times between 0 and 30 min. At the end of each holding time, the insects were quickly transferred from the heating block to 32 fl oz plastic containers with thinning apples and cardboard strips for the larvae to use to spin cocoons.

Treated larvae were stored at 3 ± 1°C for two days, removed, and kept at room conditions of 23°C, 50 to 60% RH and a 16:8 (L:D) h photoperiod. Larvae were left for one day at the above conditions, to eliminate the effects of cold stupor, before being examined for survivors by prodding with a hairbrush. Insects were considered dead if no movement was observed. Dead and surviving larvae were further observed for an additional five days. Insects that still showed no movement (excluding moribund larvae) were counted as dead. The above handling method is commonly used for CM fifth-instar mortality tests (Yokoyama et al., 1991; Neven et al., 1996). A total of 180 insects were treated in five to seven replicated runs at each time and temperature combination. Controls were placed in the block system for 30 min without heating, and afterwards they were subjected to the same conditions and analysis, as were the heat-treated insects.

Results and Discussion

Temperature Distribution in Heating Block Assembly

Experimentally determined temperatures in the block and the insect chamber (fig. 3) were obtained at different heating rates, set temperatures, and holding times. The heating was uniform, and temperature control was reasonably good (–0.2 to +0.4°C from set points). A contour plot for FEM-simulated heating and holding temperature profile without insects at the maximum rated power of the heating pads is shown in figure 4. The FEM results showed the maximum heating rate obtainable with the system to be 28.3°C/min, compared to a value of 27.4°C/min determined experimentally (data plots not shown for brevity). This difference may be accounted for by the conservative assumption of convective heat transfer at the side face and by the imperfect insulation for the block. From the measurement of the current and the voltage through the heating pads, we estimated the actual power delivered to each pad to be 249.6 W which was close to our assumed total power of 500 W. For the purpose of the analysis in visualizing different effects on heating uniformity, the difference between the measured and simulated heating rates was acceptable. As shown in figure 4, the least heated part was at the side face of the sandwich plate, away from the insect chamber. At the maximum heating rate of 28°C/min, temperature differential was < 0.7°C when heated to 50°C. This difference was reduced to < 0.1°C within 5 s of holding (fig. 4b). It is desirable to have good temperature uniformity in the treatment chamber so that all insects can be given similar exposures to the heat.

When a 20°C/min ramp was used without CM larvae, the maximum temperature differential in the block was 0.5°C. This difference decreased to < 0.1°C after 5 s of holding. During the 5 s simulated holding time (heat redistribution period), the temperature of the hottest part of the block decreased by 0.4 and 0.3°C for the 28°C/min and 20°C/min heating rates, respectively. Temperature differential was proportional to the heating rate.

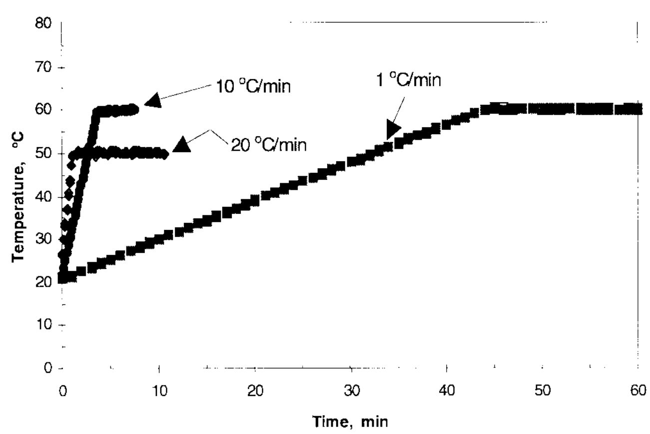
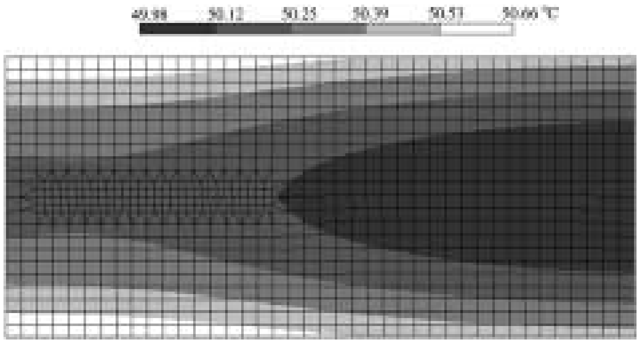
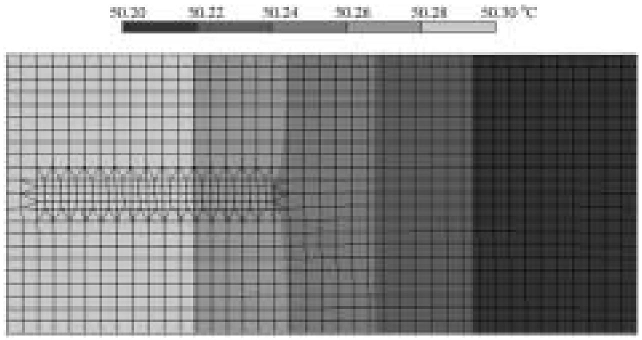


Figure 3–Experimental temperature profiles in the block heating system for insect thermal resistance study, showing different ramping rates, control at final temperatures and closeness of the two thermocouple readings.



(a)



(b)

Figure 4–Contour plot showing temperature distribution in one quadrant of the heating block without insects at maximum heating rate of 28°C/min ramp to 50°C, (a) at end of heating, (b) after 5 s holding.

Temperature of CM Larva during Heat Treatment with Heating Block System

To determine the influence of heating rates and insect mass on thermal lag, simulation results for insects heated to 50°C at 20°C/min and 5°C/min were compared. In addition, the effects of two contact conditions between the insect larva and the bottom block on the thermal lag in the insects were investigated by computer simulation. Simulated results for selected treatments are summarized in table 2. Typical temperature profile within insects during heating is demonstrated in figure 5 for simulated treatment of fifth-instar larvae in close contact with the bottom block heated at 20°C/min. The uppermost region of the insects were the least heated. After ramping to 50°C, the temperature differential between a larva's coldest spot and the part in contact with the block was as much as 4.6°C (simulation done with five insects). A holding time of 30 s was required to reduce this differential to within 0.6°C. This suggests that for treatments at high heating rates, insects may be exposed to the set holding temperature for less time than presumed. This may become critical if a high-temperature-short-time treatment method is considered for larvae and host commodity quarantine. Yokoyama and Miller (1987) reported that when oriental fruit moth larvae were placed in 15 mL glass vials and submerged in a water bath at 43 to 47°C, it took 6 to 7 min for the air temperature inside the vials to reach the test temperatures.

Table 2. Simulated temperature differential in the heating block insect treatment system during temperature ramp and hold at a 50°C set point

	Temperature differential (°C) between insect chamber wall and coldest point with or without insect*			
Treatment	0 s	30 s	60 s	120 s
28°C/min heating rate without insect	< 0.2			
20°C/min Heating Rate				
No insect	< 0.1			
1 CM in contact with bottom block	4.6	0.5	< 0.1	
5 CM in contact with bottom block	4.6	0.6	< 0.1	
1 CM in air (no contact with block)	8.6	3.3	1.2	< 0.2
5°C/min Heating Rate				
No insect	< 0.1			
5 CM in contact with bottom block	< 1.1	< 0.2		

* Coldest point without insect was at the side edge of the heating block system. Coldest point with insect was at the top part of the larva. Temperature differentials for 30, 60, and 120 s (not shown) were much less than 0.1°C.

Figure 6 shows the simulated temperature changes with time at selected points in the aluminum block, insect (air) chamber, and center of a larva during a heat treatment at 20 and 5°C/min ramps. Locations of the nodes are indicated by white dots (points A to D) in figure 5. According to the simulation, the temperature in the aluminum block increased linearly with time until the block reached the set temperature of 50°C (fig. 6a), but the temperature of the air inside the insect chamber and CM larva center lagged behind when heated at 20°C/min. At the end of the ramping period, the air and CM temperature increased asymptotically to the set temperature. However, there was little temperature differential among the block, air, and CM at the 5°C/min heating rate (fig. 6b). The maximum temperature differentials in the insect at the end of the ramping period were 4.6 and 1.1°C when heated at 20 and 5°C/min ramp rates, respectively (table 2).

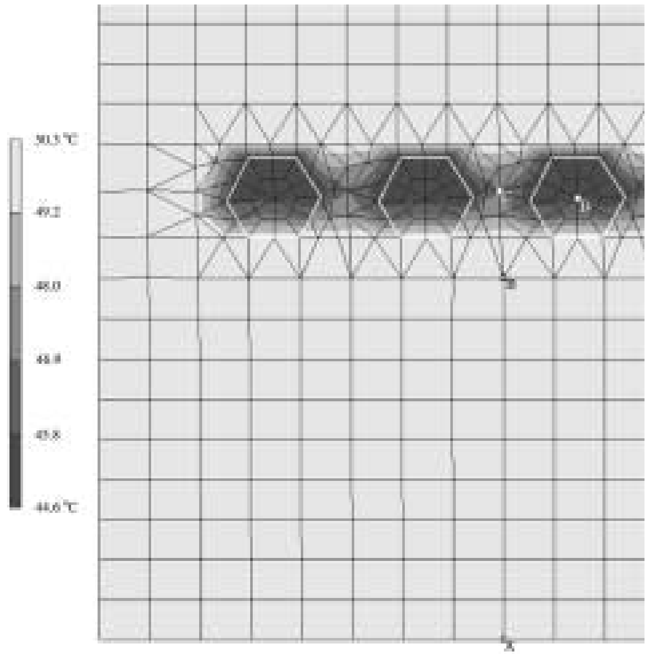


Figure 5–Heating block with codling moth enlarged to show temperature distribution in insects at the end of 20°C/min ramp to 50°C. Small circular dots (A to D) represented nodes for which temperature time histories are shown in figure 6.

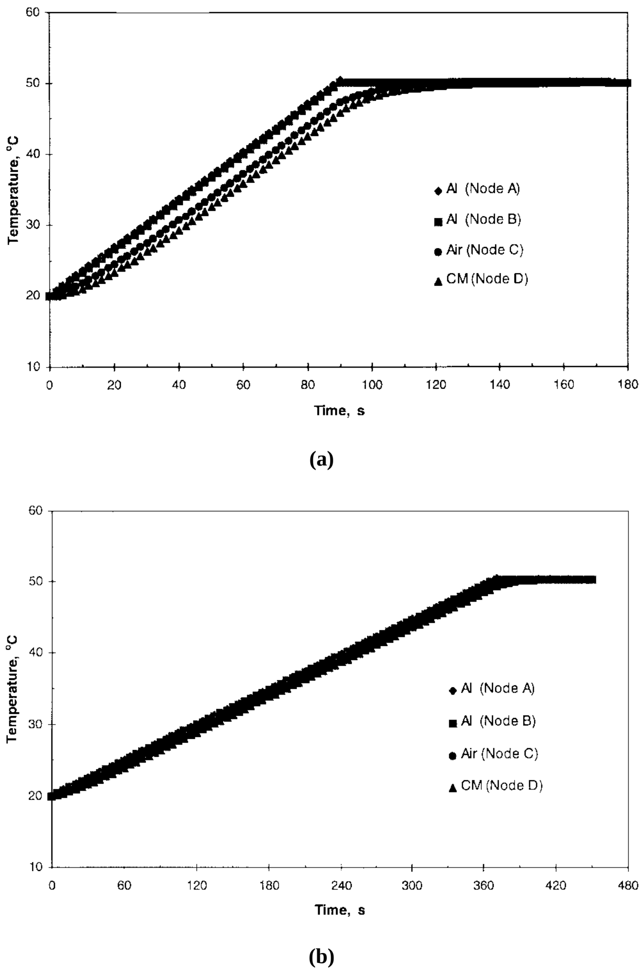


Figure 6–Temperature changes at selected nodes in aluminum block, insect (air) chamber, and center of CM during heating to and holding at 50°C (a) 20°C/min, and (b) 5°C/min. Nodes A, B (aluminum block); Node C (insect chamber), and Node D (insect center) are shown in figure 5.

There was little temperature difference between simulated treatments with five insects and with one insect for the 20°C/min heating rate (table 2). Marked difference, however, existed in temperature differential at the end of ramp and equilibration when the insects were not in contact with the aluminum block (table 2). 120 s were required to reduce the differential at 20°C/min from 8.6 to < 0.2°C during holding, when the insects had no contact with the heating blocks. Although the no-contact case was not expected in actual treatments with our system, this result does emphasize the necessity to ensure a good contact with heating surfaces to obtain accurate data for intrinsic thermal resistance of insects.

When codling moths move, they tend to stretch their bodies, reducing their diameter. The assumed characteristic diameter of CM in the simulation presents a limiting case, as many fifth instars may not grow to such a size. Weitzner and Whalon (1987) measured the head capsule width of CM first and fifth instars at 0.33 and 1.55 mm, while Chen (1999) reported values of 1.1 to 1.2 mm and 1.5 to 1.6 mm, respectively. Head capsule size, which only changes during molting, has been shown by those authors to be a good distinguishing measure of instar's width. The body (thorax and abdomen sections) diameter can, however, be reduced during movement or penetration into hosts while feeding. The largest body size (2.5 mm) measured in our laboratory in larva's resting state was used in our simulation. This dimension is more than twice the apparent larva width. Thus, the results obtained here are conservative. It can be proven from heat transfer theory that during constant temperature ramping, halving the size could reduce the temperature differential by three-fourths (Tang et al., 1991). The thermal lag will be much less for smaller instars. This may, in part, explain why the fifth instar, being the largest larva, is the most heat tolerant stage of the CM reported in the literature (Yokoyama et al., 1991).

Thermal Kinetics Study of Fifth Instar CM

Figure 7 shows the experimental data for the effect of temperature and time combinations on mortality of fifth instar CM obtained with the described heating block system. The figure also presents a semilogarithmic relationship between minimum time-temperature combinations required to completely kill fifth instar CM larvae. The dashed line in figure 7 represents the thermal-death-time curve that defines the boundary for 100% mortality in the upper right hand region of the temperature-time map. At the 20°C/min heating rate, a complete kill was obtained when heating to 48, 50, and 52°C for 20, 5, and 2 min, respectively. These results agreed reasonably well with those of Yokoyama et al. (1991) for CM, and Sharp and Chew (1987) for fruit fly larvae. In the test chamber, the air may be relatively dry. Possible evaporative cooling from the insect may reduce the body temperature, although this reduction may be small due to little air movement in the small air gap, and the moderate temperature used in the tests. The thermal death time curve obtained in our study may be slightly conservative compared to the humid condition in fruits.

The potential for successful development of an effective relatively high-temperature-short-time treatment to control insects and to minimize detrimental thermal effects on products relies on differences in the kinetics for insect inactivation and host quality degradation. The temperature dependence of the thermal resistance for fifth instar CM is

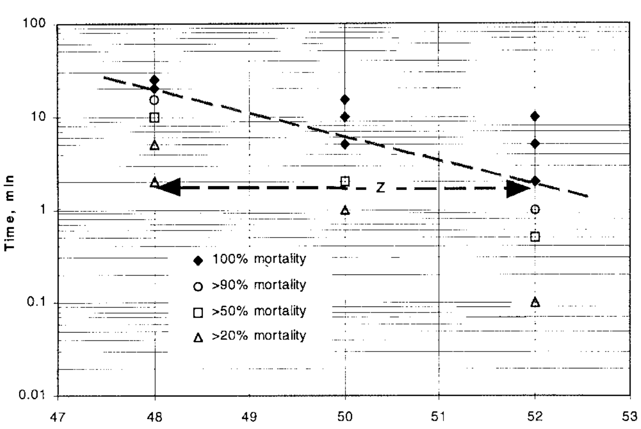


Figure 7–Thermal death time curve for fifth-instar codling moths at 20°C/min heating rate (150 to 200 larvae each point). Data points are the mean percentage mortality and were not adjusted for control mortality.

reflected by the activation energy, estimated from the following relationship (Rao and Lund, 1986):

$$E_A = \frac{2.303\,R\,T_{min}\,T_{max}}{z} \quad (8)$$

where E_A is the activation energy in J/mol, T_{min} and T_{max} are the minimum and maximum temperature in K of a test range, respectively, R is the universal gas constant (8.314 J/mol K), and z is the temperature difference corresponding to one log reduction in thermal death time (fig. 7).

The z-value and E_A for thermal destruction of fifth instar CM were estimated to be 4.0°C and 499 kJ/mol, respectively. The E_A for thermal killing of the insect is higher than that for thermal inactivation of bacterial spores (E_A = 210 – 350 kJ/mol) and much greater than that for many food quality parameters such as texture (softening), color, and flavor changes (40 to 120 kJ/mol) as reported by Lund (1977) and Rao and Lund (1986). The activation energy relates reaction rate to temperature change by the following Arrhenius relationship:

$$k = k_{ref}\, e^{-\frac{E_A}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)} \quad (9)$$

where k is the reaction rate constant at temperature T in K, and k_{ref} is the reaction rate constant in s^{-1} at the reference temperature T_{ref} in K. Based on equation 9 and the activation energies listed above, CM larvae are much more sensitive to increase in treatment temperature than product qualities. Therefore, it is possible to develop a relatively high-temperature-short-time process to thermally kill CM larvae while minimizing quality loss in the host product. The upper limit for treatment temperature and heating rate will depend upon an economical means to deliver and withdraw the required thermal energy and the uniformity of temperature rise within the product. In fact, the fundamental information on thermal resistance of CM larvae resulting from this block system is being used in our laboratory to develop effective short-time thermal treatments based on radio frequency (27.12 MHz) energy.

Conclusion

A unique experimental system was developed to heat directly insects over a wide range of controlled heating rates for insect thermal mortality studies. Finite element analyses and experimental results showed that temperature in the heating system was sufficiently uniform in the insect chamber, within ±0.3°C of the set point. The system was used to study thermal mortality of fifth instar codling moth larvae at temperatures between 48 and 52°C heated from room temperature at 20°C/min. A z-value of 4°C and an activation energy of 499 kJ/mol were obtained for the insect. The kinetic data for codling moth and other insect pests will be valuable for developing optimum thermal alternative quarantine treatments for various commodities. This system may find application among researchers involved in designing insect thermal quarantine treatments for agricultural products. Work is in progress to determine the effect of heating rates, and a combined heat and controlled atmosphere, on insect mortality using this heating system.

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