

**Thermal death kinetics and heating rate effects
for fifth-instar codling moths (*Cydia pomonella* (L.))**

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Abstract

Thermal death kinetic parameters of fifth-instar codling moths (*Cydia pomonella* (L.)) and the effect of three heating rates (1, 10 and 18°Cmin⁻¹) on larvae mortality were determined by a heating block system. The insects were heated to four temperatures (46,48, 50 and 52°C) held for predetermined periods followed by 24 hr storage at 4°C before mortality evaluation. Thermal death kinetics for fifth-instar codling moths followed a 0.5th order of kinetic reaction. Minimum time required to achieve 100% mortality of a given population decreased with temperature in a semi-logarithmic manner. No larva survived was observed in samples of 600 insects after holding at 46, 48, 50 and 52°C for 50, 15, 5 and 2 min, respectively. Activation energy for thermal kill of fifth-instar codling moths at the heating rate of 18°Cmin⁻¹ was estimated to be about 472 kJmol⁻¹. The lethal time cumulated during the ramp period was about 1.8, 0.2 and 0.1 min for the heating rates of 1, 10 and 18°Cmin⁻¹, respectively.

Keywords: Thermal death time, kinetics, heating block, heating rate, codling moth.

1. Introduction

Interest in using heat treatments to provide quarantine security against pests in fresh and stored agricultural commodities has increased in the wake of regulatory actions over the use of pesticides. Concerns about their effects on humans and the environment and implementation of the U.S. Food Protection Act of 1996 will further limit use and availability of some widely used chemical fumigants, especially the use of methyl bromide (MeBr), against codling moth in fruits and nuts (UNEP, 1995). An understanding of intrinsic mortality parameters and relationships between applied heat and its cumulative effect on both pest and commodity is necessary in determining suitability and effectiveness of an alternative heat treatment method.

Infesting pests differ very widely in tolerance to heat treatments. Thus, knowledge of the minimum required thermal energy to control infesting insects over a relatively large range of temperatures would provide flexibility for the design of suitable and effective thermal quarantine processes. Information for the thermal resistance of targeted pests also needs to be combined with the fundamental heat transfer theories and commodity quality data to develop protocols that deliver required lethal energy doses to kill infesting insects while minimizing adverse impact on the quality of the host commodity.

Several researchers have reported heat resistance of codling moth instars (Yokoyama et al., 1991; Neven, 1994; Neven and Mitcham, 1996; Neven and Rehfield, 1995; Ikediala et al., 1999). Jang (1991) observed that much of the research on application of heat treatments to obtain quarantine security has not been systematic. For example, different experimental and heat application methods have been used to assess the thermal resistance of codling moths, and reported information for codling moth or other insects are often confounded by the heat transfer phenomenon and the heat application method employed.

A common method used to determine the thermal resistance of insects is to heat the infested commodity to a selected temperature and to hold the commodity at this condition for pre-determined times. The information obtained may be applicable only to the tested product and the specific test conditions. It is difficult to extract true information about the insect's intrinsic resistance to heat because this information is confounded with the effect of heat transfer, which in turn is dependent on the heating methods, thermal properties and size of the products, as well as position of insects in the host material. Furthermore, a large amount of reported data for pests are in the form of percent lethality, which only represents relative thermal resistance of the insects. These data may not be directly useful when another commodity is considered for the same pest. Thus, a method that provides intrinsic kinetic data for a target insect is needed so that the mortality data can be used for developing different thermal treatments.

Heating rate is believed to have a significant effect on insect metabolism and physiological adjustment to the heat treatment (Evans, 1986; Neven, 1998a,b). Neven (1998a) reported that codling moth larvae might experience thermal conditioning and acclimation to the heat between 0.13 and 0.2°Cmin⁻¹ heating rates. Consequently, longer holding time is required at a final temperature in order to achieve the same mortality at a slower heating rate. For conventional heating, the heating rates in the interior of commodities ranged between 0.05 and 2°Cmin⁻¹, depend on heating methods, type and size of commodity and the end temperature (Wang et al., 2001b). In addition, the heating rate at the interior of a commodity decreases with time under a constant treatment condition due to decreasing temperature difference between the heating medium and the fruit. As a result, conventional heat treatments typically take long times to achieve required security against insects. Most insects may have adequate time to adapt to the heat and increase thermal resistance (Waddell et al., 2000).

Fast heating methods (10-20° Cmin⁻¹ heat rates) based on radio frequency (RF) and microwave energy have been proposed to control insect pests in commodities to replace chemical fumigation (Nelson and Payne, 1982; Ikediala et al., 1999; 2001; Tang et al., 2000; Wang et al., 2001a). Recently, Ikediala et al. (2001) and Wang et al. (2001a) reported thermal treatment methods using 27 MHz RF energy to control codling moths in cherries and walnuts without significantly reducing product quality. Therefore, there is a need to study the effect of all possible heating rates on the thermal death kinetics of insects.

The objectives in this research were to study the thermal death time (TDT) kinetics of fifth-instar codling moths and to determine the effect of heating rates on mortality of this insect pest.

2. Materials and methods

2.1 Heating block system

A computer-controlled heating block system which provided heating rates from 0.1 to 20°Cmin⁻¹ was developed for studying thermal death kinetics of insect pests. Details of this heating system have been described in Ikediala et al. (2000) and an improved version in Wang et al. (2001c). The death rate kinetics and the effect of heating rates on thermal mortality of insects were investigated using this heating system.

2.2 Heat treatment of codling moth larvae and mortality analyses

Fifth-instar codling moths, *Cydia pomonella* (L.), were used in experimental heat treatments. Yokoyama et al. (1991) showed this developmental stage to be the most heat tolerant. Codling moth larvae were obtained from the USDA-ARS Yakima Agricultural Research

Laboratory, Wapato, WA. Before each heat treatment 200 larvae were extracted from artificial diet (Toba and Howell, 1991) and placed in the heating block chamber. The system temperature was then ramped up at one of three heating rates (1, 10 and 18°Cmin⁻¹) to 46, 48, 50 and 52°C. Insects were held at those final temperatures for three to five different periods that varied between 0.5 min at 52°C and 10 min at 46°C. These holding periods would allow a wide range of the mortality levels including 100%. The heating rate of 1 °Cmin⁻¹ was selected to simulate the slow heating for fruits using conventional heat treatments such as forced hot air and hot water baths and the heating rates of 10 and 18°Cmin⁻¹ were used to simulate the fast heating for fruits using radio frequency and microwave energies.

To compare the effect of heating rates on the insect mortality, four temperature-time combinations, 46°C+40 min, 48°C+5 min, 50°C+2 min and 52°C+1 min, were selected just below a complete kill level as described by the TDT curves (defining minimum temperature-time required to achieve 100% mortality in a given sample) developed at the heating rate of 18°Cmin⁻¹.

Control larvae were placed in the unheated block chamber for 50 min. For each temperature and holding time combination, including controls, 200 larvae were treated at a time and all treatments were repeated three times for a total of 600 larvae.

At the end of each treatment, the power to the heating block was turned off and the insects were immediately transferred to a plastic container (less than 10 sec). Cardboard strips were provided for pupation sites. Because we anticipated that commercial treatments would include rapid post-treatment cooling of cherries to minimize the effect on product quality, the treated larvae were immediately moved to cold storage at 4°C and stored at this temperature for one day. After the cold storage, the larvae were held at 23°C, 60% RH and a 16:8 (L:D) h

photo-period for one day to minimize the effect of cold stupor before examination. Insects were considered dead if no movement was observed. Moribund and surviving larvae were observed for additional five days. The level of pupation or adult emergence was not used in the evaluation because the time to pupation and adult emergence took several weeks (Retan, 1984).

Mortality was calculated as the percentage of dead larvae relative to total treated larvae for each treatment. Mean values and standard deviations were calculated from three replications for each temperature-time combination.

2.3 Insect thermal kinetic modeling

Different methods have been used to analyze thermal resistance of insects. Probit analysis is the most common method. In relation to our subject, it is based on the assumption that the frequency of individual deaths in an insect population under constant temperature follows the standard normal distribution with cumulative probability of death increasing with time (Finney, 1971; Sokhansanj et al., 1990; Tang and Sokhansanj, 1993). The probit analysis, however, only provides information on the relative efficacy of a given quarantine treatment dose (e.g., probit 9 criteria requires a 99.9968% mortality). Although this is useful for confirming quarantine treatments effectiveness, it may not be best suited for developing new thermal treatment conditions outside the range of experimental conditions. The analysis also does not give the kinetic parameters for insect thermal mortality nor provide sufficient information from which new or other temperature-time combinations can be chosen. Thomas and Mangan (1997) critically reviewed several models for Mexican fruit flies. They recommended the use of a thermal dynamic kinetic model for estimating the efficacy of quarantine treatments in developing new treatment methods, but recommended use of the traditional probit analysis for confirming

estimates. Jang (1986; 1991) detailed the advantages of the kinetic model for determining the thermal death rate parameters of fruit flies. Earlier, the use of a probit 9 mortality as criterion to ensure quarantine treatment security of fruits infested by fruit flies and other pests has been questioned by Landolt et al. (1984).

A rather elaborate theory of Thermobacteriology has been developed based on thermal kinetic model and TDT lethality curves for thermally inactivating pathogens in canned foods (Stumbo, 1973). The theory and concepts, which evolved from the thermal death rate calculations and the classical thermal kinetic model for describing thermal mortality of microorganisms, have been readily extended to study thermal mortality of insects. Several researchers have suggested that the logarithmic order of death was not always followed by microorganisms (Alderton and Snell, 1970; Moats, 1971; King et al., 1979). Jang (1986; 1991) used a modified logarithmic formula derived by Alderton and Snell (1970) to model thermal mortality of fruit flies. Thus, the knowledge of the fundamental kinetics for thermal death of insects allows the prediction of lethal times over a range of temperatures. Tang et al. (2000) described the TDT concept in details and its applicability to model insect pest heat destruction kinetics. A significant advantage of the thermal kinetic model, whenever suitable to model death rates over the probit method, is the ability to predict the efficacy of a thermal process based on temperature-time history in host materials.

In developing a kinetic model to describe thermal kill of codling moth larvae, we used a classic kinetic model approach in which we determined the order of reaction and then determined the activation energy based on the dependence of reaction rate on temperature. In this analysis, the ratio change of insect survivals (N) to initial insect number (N_0) during thermal treatments was modeled as following the fundamental kinetic model:

$$\frac{d(N/N_0)}{dt} = -k(N/N_0)^n \quad (1)$$

where n is the kinetic order of reactions. The integration form of Eq. (1) was obtained for different reaction orders as follows:

$$\begin{aligned} \ln(N/N_0) &= -kt + c & (n = 1) \\ (N/N_0)^{1-n} &= -kt + c & (n \neq 1) \end{aligned} \quad (2)$$

A linear regression analysis was performed in this study for the zero order, half order, first order, 1.5th order and second order of reactions. The best-fitted line was determined by comparing the coefficients of determination (R^2) for all the treated temperatures. After the reaction order was determined and the corresponding best-fit values of k and c were obtained, the model was used to estimate the lethal time LT_{95} , LT_{99} , $LT_{99.83}$ and $LT_{99.9968}$.

The activation energy for thermal inactivation of test larvae was estimated from the relationship between k and T on an Arrhenius plot (Stumbo, 1973; Tang et al., 2000):

$$k = k_{ref} e^{\frac{-E_A}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right)} \quad (3)$$

where T is the absolute temperature (K), k_{ref} is the reaction rate constant at the reference temperature T_{ref} (K), E_A is the activation energy (Jmol^{-1}), and R is the universal gas constant ($8.314 \text{ Jmol}^{-1} \text{ K}^{-1}$).

The activation energy E_A for thermal kill of codling moths was also estimated from a TDT curve (Tang et al., 2000):

$$E_A = \frac{2.303RT_{min}T_{max}}{z} \quad (4)$$

where T_{min} and T_{max} are the minimum and maximum temperatures (K) of a test range, respectively. z is the degree of temperature increase to result in one log reduction in time on a

TDT curve. That is, the z value in the theory of Thermobacteriology is related to the value of rate constant and activation energy in the classical reaction kinetic theory.

Once the z value, or k and E_A values, for a target insect pest are determined, the accumulated temperature-time effect of a thermal treatment with a known temperature history on reduction of the organism can then be predicted with a good accuracy (Tang et al., 2000). This method has been the basis for calculating the thermal processing times for commercial food thermal pasteurization and sterilization processes (Stumbo, 1973).

2.4 Cumulative effect of ramp period

Different heating rates resulted in different ramp periods to reach the same holding temperature. It is possible to estimate the cumulative effect (corrected holding time) due to the temperature ramp periods. For closed to 1st order kinetics, we may use the following relationship to approximately determine the cumulative effect for any given temperature-time history (Tang et al., 2000), in terms of equivalent total lethal time M_{accum} (min) at a reference temperature, T_{ref} (°C):

$$M_{accum} = \int_0^t 10^{\frac{(T(t)-T_{ref})}{z}} dt \quad (5)$$

The temperature-time history $T(t)$ for the treatments used in this study is presented in Fig. 1, where T_0 is the starting temperature (°C); where T_h is the holding temperature (°C); t_0 and t_1 are the times (min) at the end of the ramp and the holding, respectively. During the ramp period, the temperature is a linear function of time, and can be expressed as $T(t) = T_0 + \alpha t$, where α is the heating rate (°Cmin⁻¹). With this relationship and using the holding temperature as the reference temperature ($T_{ref} = T_h$), Eq. (5) can be directly integrated between the limits $t=0$ and $t=t_1$ into:

$$M_{accum} = \frac{z}{2.303\alpha} \left[1 - 10^{-\frac{T_0 - T_h}{z}} \right] + (t_1 - t_0) \quad (6)$$

where the first term represents the equivalent lethal time at the holding temperature accumulated during the ramp period, while the second term corresponds to the actual holding time. The above relation can be used to compare treatments at different heating rates, holding times and temperatures (Tang et al., 2000). An average z value of 4°C was used based on the results of Ikediala et al. (2000) and the initial temperature was 22°C . The corrected treatment times corresponding to the three heating rates for the holding temperatures of 46, 48, 50 and 52°C were compared.

3. Results and Discussion

3.1 Kinetics of codling moth mortality

The survival in unheated controls was high ($92.4 \pm 2.8\%$), suggesting negligible effect of shipping and handling. Table 1 shows the coefficients of determination (R^2) for different reaction orders for all the treated temperatures to kill the codling moth larvae. The 1st order reaction was best suited to describe thermal mortality kinetics for fifth-instar codling moths at treatment temperatures above 48°C . But for the overall tested temperature range between 46 and 52°C , the 0.5th order reaction was most applicable. The 0.5th order reaction was also found most suitable for fifth-instar navel orangeworms (Wang et al., 2001c).

The thermal mortality curves for fifth-instar codling moths were shown in Fig. 2 together with the best fit curves based on the 0.5th-order reaction. The thermal death constants for the 0.5th-order reaction model were presented in Table 2. The established thermal death kinetic model was further used to predict the lethal times (LT) to reach 95%, 99%, 99.83% and

99.9968% mortality (Table 3). Table 3 also lists the observed minimum holding times at each temperature to achieve 100% mortality in tested samples. Complete kill in samples of 600 insects was obtained after holding at 46, 48, 50 and 52°C for 50, 15, 5 and 2 min, respectively. The predicted values for $LT_{99.83}$ and $LT_{99.9968}$ were close to the observed results with samples of 600 insects. The discrepancy might have been caused mostly by the limited resolution due to experimental holding time intervals used in experiments at each holding temperature (Fig. 2). As expected, percent mortality increased with increasing temperature and holding time. It is interesting to note in Table 3 that only about 10% extra time was needed to increase the efficacy of a heat treatment from 99% mortality to 99.9968% (Probit 9) when fifth-instar codling moths were fully exposed to a constant temperature.

Fig. 3 shows a TDT curve at the heating rate of $18^{\circ}\text{Cmin}^{-1}$ that defines the minimum temperature and time requirements with the selected time intervals to achieve 100% kill of samples of 600 insects. The z value was estimated to be 4.2°C from the TDT curve. The observed exposure time for 100% mortality of all 600 test insects corresponded to the estimated lethal times needed to achieve at least 99.83% mortality at a given temperature. The relationship ($\log t = 12.41 - 0.23 T$) between the observed exposure times to achieve 100% insect mortality and the treated temperatures was obtained by linear regression with $R^2 = 0.996$. The value of k obtained from 0.5th order reaction relationship followed an Arrhenius relationship (Eq. (2)) expressed as $\log k = 75.22 - 24.64 * 1000/T$ with $R^2 = 0.995$ (Fig. 4).

3.2 Activation energy

The activation energy for thermal kill of fifth-instar codling moth was calculated from Eqs. (3) and (4) based on z value of 4.2°C to be 472 and 473 kJmol^{-1} , respectively. Table 4

compares the activation energy (E_A) of different insect pests, microorganisms and quality parameters of food commodities. The activation energy for thermal kill of the insect ranged from 400 to 958 kJmol⁻¹. The E_A values for fifth-instar codling moths obtained in this study compared well with those of fifth-instar navel orangeworm (Wang et al., 2001c) and of the four species of fruit flies reported by Jang (1986; 1991) and Moss and Chan (1993). In general, the activation energy for thermal kill of insects was slightly greater than that for thermal inactivation of pathogenic microbial spores and much greater than for softening and many other quality changes in food commodities due to heat (Table 4). Like other insects, codling moth larvae were much more sensitive to increase in treatment temperatures than most fruit quality aspects. This provides opportunity for the possible development of relatively high-temperature-short-time thermal treatment processes that may kill insects while having minimal impact on product quality (Tang et al., 2000)

3.3 Effect of heating rates on insect mortality

Table 5 highlights the effect of three heating rates on insect mortality under four temperature-holding time combinations (46°C+40 min, 48°C+5 min, 50°C+2 min and 52°C+1 min). Using the heating rate of 1°Cmin⁻¹, all four treatments achieved 100% kill, whereas none of the four treatments achieved 100% kill when using the heating rate of 18°Cmin⁻¹ (Table 5). The added thermal mortality in the treatment using slow heating rates, however, may be the result of the extended ramp period in which the insects were exposed to the elevated temperature. For example, the ramp time from 22°C to reach 52°C was 30 min when heating at 1°Cmin⁻¹ compared to 1.7 min when heating at 18°Cmin⁻¹.

The cumulated lethal time during ramp periods (M_{accum}) for three heating rates from initial 22°C to the set temperatures was calculated using Eq. (5) and listed in Table 6. The lethal time cumulated during the ramp period was about 1.8, 0.2 and 0.1 min (equivalent to holding time at the end temperature) for the heating rates of 1, 10 and 18°Cmin⁻¹, respectively. Those values were not affected by the end temperatures. Adding the actual holding time listed in Table 5 to the cumulated lethal time during the ramp period suggested that the corrected treatment times at each temperature increased with the reduction in the heating rates. The cumulated lethal time had a significant effect on the short holding time at high temperatures. The incomplete kill of all four treatments at 18°Cmin⁻¹ heating rate might be due to little lethality accumulated during the ramp period at the 18°Cmin⁻¹. The large difference in the mortality (Table 5) between 10 and 18°Cmin⁻¹ may not have been caused by the small difference in the calculated cumulative lethal time. Explanation for the discrepancy requires further investigation.

This analysis has shown that treatments in which different heating rates were used to achieve the same holding temperature were not equivalent, and thus did not impart the same heat lethality. With slow heating rates, the insects would have been exposed to the lethal temperatures for longer time than with treatments using faster rates. The contribution of the ramp period can be very significant if the heating rate is small.

Neven (1998a) observed that within heating rates between 0.13 and 0.2 °Cmin⁻¹, the slower the rate of heating, the longer the codling moth larvae had to be exposed to the final treatment temperature to achieve 95% mortality. Lester and Greenwood (1997) also reported that a low heating rates and long exposure of insects to elevated but non-lethal temperatures (<42°C) may condition insects such that subsequent treatment at lethal temperatures above 42°C are less effective. This implies that higher heating rate should provide greater mortality (required smaller

lethal time) because of a lack of non-lethal temperature conditioning of the insects. In this study, the total accumulated lethality required for 100% kill of the larvae appeared to be slightly higher at $1^{\circ}\text{Cmin}^{-1}$ than at $18^{\circ}\text{Cmin}^{-1}$. This is contrary to what was observed by Neven (1998a). It is clear that the heating rates used in this study were much larger than those used by the above author and that the relatively long ramp time at even the lowest heating rate ($1^{\circ}\text{Cmin}^{-1}$) tested in this study was not adequate to allow insects to develop thermotolerance.

4. Conclusions

The heating block system was suitable for determining experimental data of temperature and heating rate effects on insect susceptibility to heat. Complete kill of 600 insects was achieved at a heating rate of $18^{\circ}\text{Cmin}^{-1}$ with a minimum exposure time of 50, 15, 5 and 2 min at 46, 48, 50 and 52°C , respectively. The fundamental 0.5^{th} reaction model was suited for predicting the thermal death kinetics of codling moth larvae. The activation energy for thermal kill of 5th-instar codling moth was about 473 kJmol^{-1} both from TDT curve and Arrhenius plot. The lethal time accumulated during ramp period to the end-point temperature was about 1.8, 0.2 and 0.1 min for the heating rates of 1, 10 and $18^{\circ}\text{Cmin}^{-1}$, respectively. The faster heating rate tended to lead to a longer holding time at the end temperatures to achieve similar mortality of codling moth larvae compared to the slower rate. Fifth-instar codling moths were not able to increase the thermal tolerance with a decrease in the heating rate in the tested range. The methods and concepts described in this report may be extended to study other infesting pests of commodities for which the heat treatment is being considered as an alternative quarantine treatment.

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References

- Alderton, G., Snell, N., 1970. Chemical states of bacterial spores: Heat resistance and its kinetics at intermediate water activity. *Applied Microbiology* 19, 565-572.
- Evans, D.E., 1986. The influence of rate of heating on the mortality of *Rhyzopertha dominica* (L.) (Coleoptera: Bostrychidae). *Journal of Stored Product Research* 23, 73-77.
- Finney, D.J., 1971. *Probit Analysis*. 3rd ed. Cambridge University Press, Cambridge, UK.
- Ikediala, J.N., Hansen, J., Tang, J., Drake, S.R. and Wang, S., 2001. Development of saline-water-immersion technique with RF energy as a postharvest treatment against codling moth in cherries. *Postharvest Biology and Technology* (in press).
- Ikediala, J.N., Tang, J., Neven, L.G., Drake, S.R., 1999. Quarantine treatment of cherries using 915MHz microwaves: Temperature mapping, codling moth mortality and fruit quality. *Postharvest Biology and Technology* 16, 127-137.
- Ikediala, J.N., Tang, J., Wig, T., 2000. A heating block system for studying thermal death kinetics of insect pests. *Transactions of the ASAE* 43, 351-358.
- Jang, E.B., 1986. Kinetics of thermal death in eggs and first instars of three species of fruit flies (Diptera: Tephritidae). *Journal of Economic Entomology* 79, 700-705.
- Jang, E.B., 1991. Thermal death kinetics and heat tolerance in early and late third instars of the oriental fruit fly (Diptera: Tephritidae). *Journal of Economic Entomology* 84, 1298-1303.
- King, A.D., Bayne, H.G., Alderton, G., 1979. Nonlogarithmic death rate calculations for *Byssochlamys fulva* and other microorganisms. *Applied Environmental Microbiology* 37, 596-600.

- Landolt, P.J., Chambers, D.L., Chew, V., 1984. Alternative to the use of probit 9 mortality as a criterion for quarantine treatments of fruit fly (Diptera: Tephritidae)-infested fruit. *Journal of Economic Entomology* 77, 285-287.
- Lester, P.J., Greenwood, D.R., 1997. Pretreatment induced thermotolerance in lightbrown apple moth (Lepidoptera: Tortricidae) and associated induction of heat shock protein synthesis. *Journal of Economic Entomology* 90, 199-204.
- Lund, D.B., 1977. Design of thermal processes for maximizing nutrient retention. *Food Technology* 31, 71-78.
- Moats, W.A., 1971. Kinetics of thermal death of bacteria. *Journal of Bacteriology* 105, 165-171.
- Moss, J.I., Chan, H.T., 1993. Thermal death kinetics of Caribbean fruit fly (Diptera: Tephritidae) embryos. *Journal of Economic Entomology* 86, 1162-1166.
- Nelson, S.O., Payne, J.A., 1982. RF dielectric heating for pecan weevil control. *Transactions of the ASAE* 31, 456-458.
- Neven, L.G., 1994. Combined heat treatments and cold storage effects on mortality of fifth-instar codling moth (Lepidoptera: Tortricidae). *Journal of Economic Entomology* 87, 1262-1265.
- Neven, L.G., 1998a. Effects of heating rate on the mortality of fifth-instar codling moth (Lepidoptera: Tortricidae). *Journal of Economic Entomology* 91, 297-301.
- Neven, L.G., 1998b. Respiratory response of fifth-instar codling moth (Lepidoptera: Tortricidae) to rapidly changing temperatures. *Journal of Economic Entomology* 91, 302-308.
- Neven, L.G., Mitcham, E.J., 1996. CATTS (Controlled Atmosphere/Temperature Treatment System): A novel tool for the development of quarantine treatments. *Journal of American Entomology* 42, 56-59.

- Neven, L.G., Rehfield, L.M., 1995. Comparison of pre-storage heat treatments on fifth-instar codling moth (Lepidoptera: Tortricidae) mortality. *Journal of Economic Entomology* 88, 1371-1375.
- Rao, M.A., Lund, D.B., 1986. Kinetics of thermal softening of foods - a review. *Journal of Food Process Preservation* 10, 311-329.
- Retan, A.H., 1984. The codling moth. Extension Bull. 1264. Cooperative Extension, College of Agriculture and Home Economics, Washington State University, Pullman, WA, USA.
- Sokhansanj, S., Wood, H.C., Venkatesan, V.S., 1990. Simulation of thermal disinfestation of hay in rotary drum dryers. *Transactions of the ASAE* 33, 1647-1651.
- Stumbo, C.R., 1973. *Thermobacteriology in Food Processing*. Academic Press Inc., New York.
- Tang, J., Ikediala, J.N., Wang, S., Hansen, J.D., Cavalieri, R.P., 2000. High-temperature-short-time thermal quarantine methods. *Postharvest Biology and Technology* 21, 129-145.
- Tang, J., Sokhansanj, S., 1993. Drying parameter effects on lentil seed viability. *Transactions of the ASAE* 36, 855-861.
- Thomas, D.B., Mangan, R.L., 1997. Modeling thermal death in the Mexican fruit fly (Diptera: Tephritidae). *Journal of Economic Entomology* 90, 527-534.
- Toba, H.H., Howell, J.F., 1991. An improved system for mass-rearing codling moths. *Journal of the Entomological Society of British Columbia* 88, 22-27.
- UNEP. 1995. Montreal Protocol on Substances That Deplete the Ozone Layer. Report of methyl bromide technical options committee: 1994 assessment. United Nations Environmental Program, Ozone Secretariat, Nairobi, Kenya.

- Waddell, B.C., Jones, V.M., Petry, R.J., Sales, F., Paulaud, D., Maindonald, J.H., Laidlaw, W.G., 2000. Thermal conditioning in *Bactrocera tryoni* eggs (Diptera: Tephritidae) following hot-water immersion. *Postharvest Biology Technology* 21, 113-128.
- Wang, S., Ikediala, J.N., Tang, J., Hansen, J.D., Mitcham, E., Mao, R., Swanson, B., 2001a. Radio frequency treatments to control codling moth in in-shell walnuts. *Postharvest Biology and Technology* 22, 29-38.
- Wang, S., Tang, J., Cavalieri, R., 2001b. Modeling fruit internal heating rates for hot air and hot water treatments. *Postharvest Biology and Technology* 22, 257-270.
- Wang, S., Tang, J., Johnson, J.A., Hansen, J.D., 2001c. Thermal death kinetics of 5th-instar navel orangeworm (Lepidoptera: Pyralidae). *Journal of Stored Product Research* (in review).
- Yokoyama, V.Y., Miller, G.T., Dowell, R.V., 1991. Response of codling moth (Lepidoptera: Tortricidae) to high temperature, a potential quarantine treatment for exported commodities. *Journal of Economic Entomology* 84, 528-531.

Table 1 Estimation of the best kinetic order (n) for the thermal kill of fifth-instar codling moths at four temperatures by comparing the coefficient of determination (R^2)

Temperatures (°C)	R^2 for different order n				
	$n=0$	$n=0.5$	$n=1$	$n=1.5$	$n=2$
46	0.991	0.954	0.663	0.479	0.460
48	0.868	0.965	0.885	0.492	0.412
50	0.735	0.857	0.972	0.876	0.858
52	0.819	0.957	0.940	0.789	0.769

Table 2. Thermal death constants for 0.5th order reaction model for fifth-instar codling moth at four temperatures and the heating rate of 18°Cmin⁻¹

Temperature (°C)	Thermal death constants of $\left(\frac{N}{N_0}\right)^{0.5} = kt + c$	
	$k \pm \text{S.E.}$	$c \pm \text{S.E.}$
46	0.0189±0.0024	1.0555±0.0984
48	0.0691±0.0066	0.9584±0.0869
50	0.2016±0.0581	0.9401±0.2175
52	0.5056±0.0620	0.9488±0.1013

Table 3 Comparison of lethal times (LT, min) obtained by experiments and 0.5th order kinetic models (Eq. 5) for fifth-instar codling moths at four temperatures and the heating rate of 18°Cmin⁻¹, followed by 24 hr cold storage at 4°C

Temp. (°C)	Observed 100% mortality for 600 insects, min	0.5 th order kinetic model			
		LT ₉₅	LT ₉₉	LT _{99.83}	LT _{99.9968} (probit 9)
46	50	44.0	50.6	53.7	55.6
48	15	10.6	12.4	13.3	13.8
50	5	3.6	4.2	4.5	4.6
52	2	1.4	1.7	1.8	1.9

Table 4. Comparisons of activation energies of thermal kill of insects and microorganisms with that of food quality changes due to heat treatments.

Insects/Materials	Temperature Range (°C)	Activation Energy E_A (kJmol ⁻¹)	Source
<i>Mediterranean fruit fly</i>			
Eggs	45-47	784	Jang (1986)
1 st instar	45-48	656	Jang (1986)
<i>Melon fly</i>			
Eggs	43-46	518	Jang (1986)
1 st instar	45-48	650	Jang (1986)
<i>Oriental fruit fly</i>			
Eggs	43-46	958	Jang (1986)
1 st , early and late 3 rd instar	43-48	209-401	Jang (1986; 1991)
Caribbean fruit fly (eggs)	37-42	440	Moss and Chan (1993)
	43-50	445	Moss and Chan (1993)
Queensland fruit fly (eggs)	42-48	538*	Waddell et al. (2000)
Navel orangeworm (fifth-instar)**	46-54	510-520	Wang et al. (2001c)
Codling moth (fifth instar):**	46-52	473	This study (from TDT)
	46-52	472	This study (from $k-T$)
Quality (texture – softening or firmness, color, flavor, etc.)			Lund (1977);
	50-70	42-126	Rao and Lund (1986)
Microorganisms (spores)	100-130	222-502	Lund (1977)

* Estimated by the authors from the reported data

** Parameter obtained at 18°Cmin⁻¹ heating rate.

Table 5. Mortality (%) of fifth-instar codling moths after heat treatments with three different heating rates from 22°C and holding for selected periods (3 replicates), followed by 24 hr cold storage at 4°C

Temperature + Holding time	Mortality (%) at heating rates		
	1 °Cmin ⁻¹	10 °Cmin ⁻¹	18 °Cmin ⁻¹
46°C+40 min	100 (24)*	100 (2.4)	87.4±8.6 (1.3)
48°C+5 min	100 (26)	91.3±6.2 (2.6)	71.0±9.2 (1.4)
50°C+2 min	100 (28)	97.3±1.9 (2.8)	92.5±0.2 (1.6)
52°C+1 min	100 (30)	100 (3.0)	90.5±6.4 (1.7)

* Value in the parenthesis indicates the ramp time to reach the targeted temperature in min

Table 6. The cumulated lethal time (min) during the ramp periods with three different heating rates from initial 22°C to the set temperatures.

Set temperatures (°C)	Cumulated lethal time (min) at heating rates		
	1 °Cmin ⁻¹	10 °Cmin ⁻¹	18 °Cmin ⁻¹
46	1.8	0.2	0.1
48	1.8	0.2	0.1
50	1.8	0.2	0.1
52	1.8	0.2	0.1

Figure Captions

Fig. 1. Typical temperature-time history used in this study.

Fig. 2. Thermal mortality curve of fifth-instar codling moths at different temperatures and the heating rate of $18^{\circ}\text{Cmin}^{-1}$. Each point represents 600 larvae and the lines were obtained by regression using a 0.5th order reaction model. N_0 and N stand for initial and survival insect numbers.

Fig. 3. Thermal-death-time (TDT) curve for 600 fifth-instar codling moths at a heating rate of $18^{\circ}\text{Cmin}^{-1}$. The straight line ($\log t = 12.41 - 0.23 T$) was obtained by linear regression ($R^2=0.996$).

Fig. 4. Arrhenius plot for temperature effects on thermal death rates of fifth-instar codling moths. The straight line ($\log k = 75.22 - 24.64 \cdot 1000/T$) was obtained by linear regression ($R^2=0.995$).

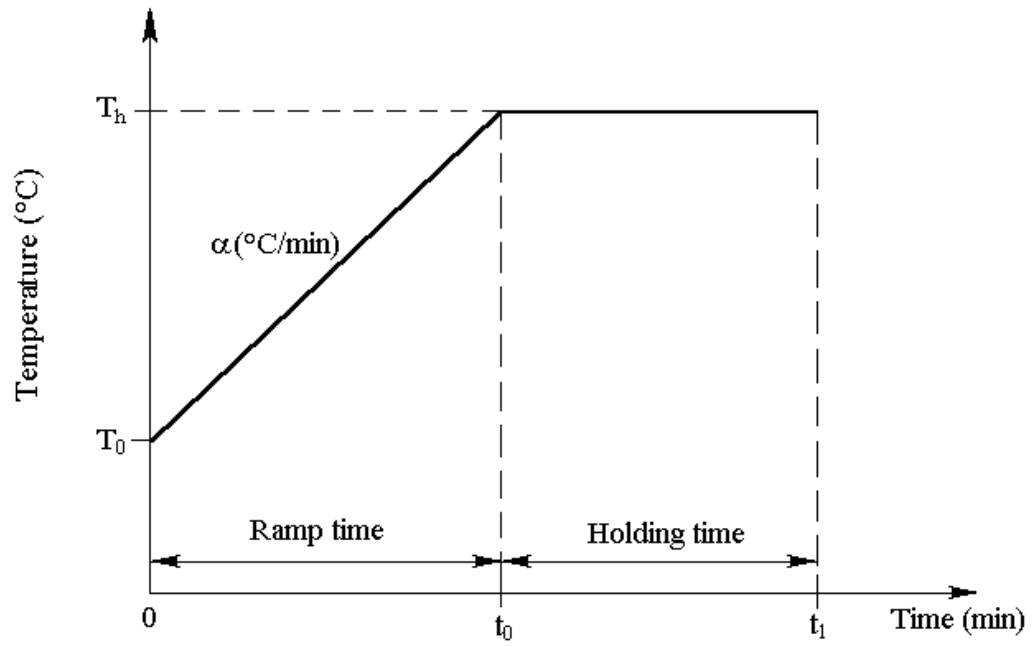


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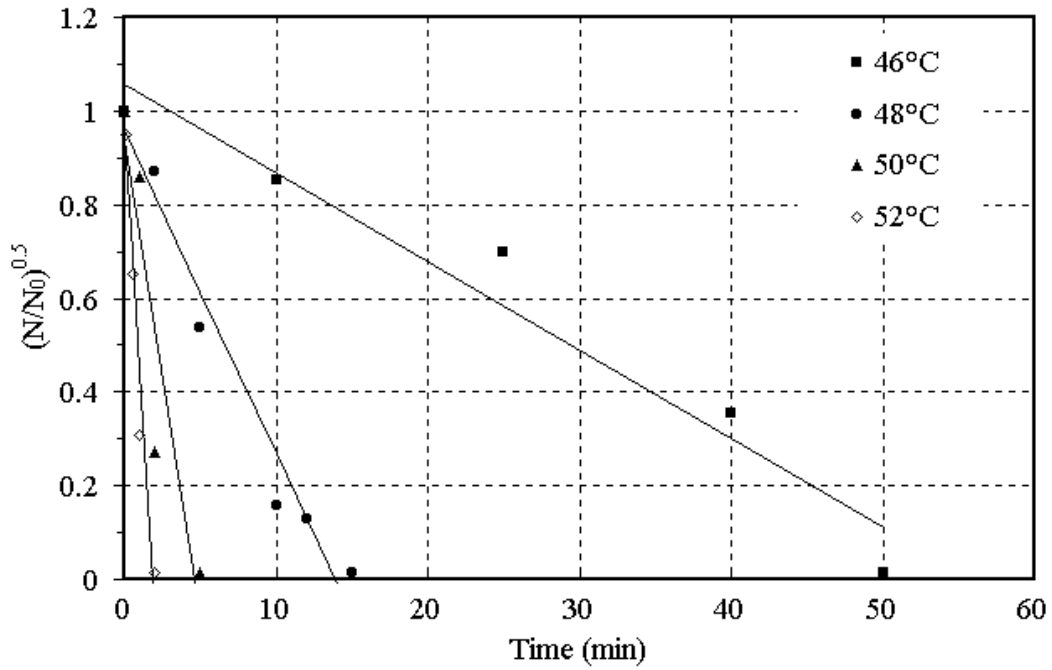


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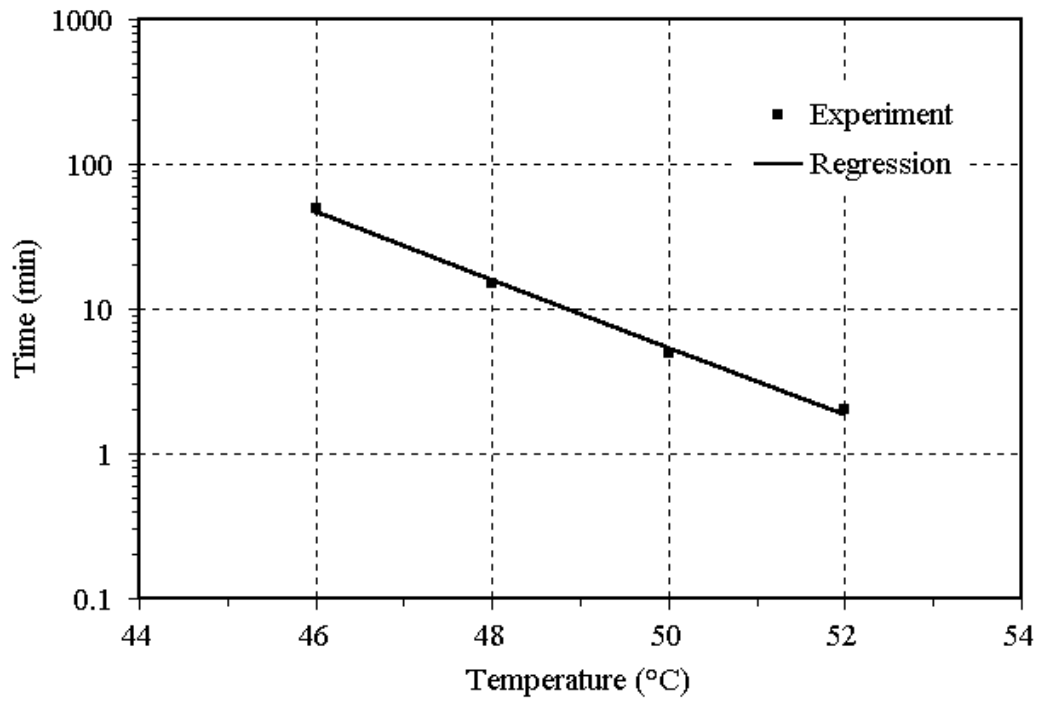


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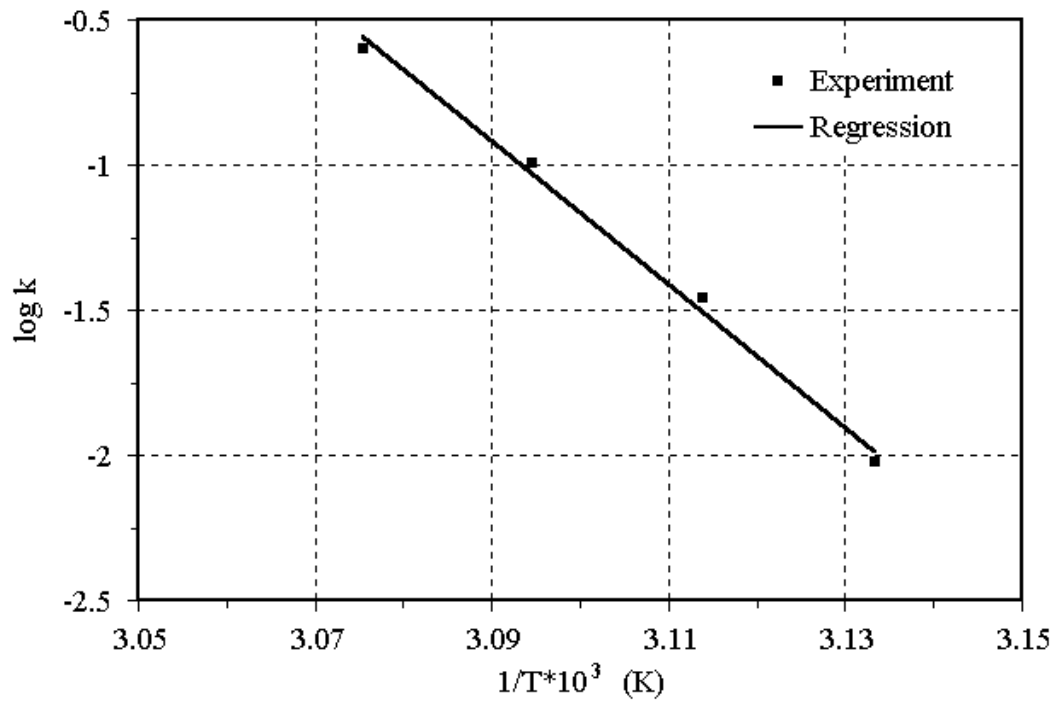


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