Development of a novel thermal death kinetic model for predicting stage-specific survival of the confused flour beetle, *Tribolium confusum* (Jacquelin du Val), during heat treatment

Dhanaraj Boina[a], Bhadriraju Subramanyam[b], and Sajid Alavi[b]
[a]Department of Entomology, [b]Department of Grain Science and Industry, Kansas State University, Manhattan, Kansas 66506
E-mail: drboina@ksu.edu

Abstract

The eggs, young larvae (neonates), old larvae, pupae, and adults of the confused flour beetle, *Tribolium confusum* (Jacquelin du Val), were exposed to 50-60ºC to identify the most heat tolerant stage. The most heat tolerant stage was exposed to 46-60ºC for developing and validating a novel thermal death kinetic model. Old larvae were consistently the most heat tolerant stage at 50, 54, 58, and 60ºC. An instantaneous *D*-value, showing one log reduction in larval survival as a function of temperature, was calculated because survival of old larvae was nonlinear over time. The relationship between instantaneous *D*-values and temperature also was nonlinear. The model satisfactorily predicted survival of old larvae exposed to a slow and a fast rate of heating during actual facility heat treatments.

Introduction

Methyl bromide, a space fumigant used in food-processing facilities, will be phased out in the United States by 2005. The use of elevated temperatures (50-60ºC for 24-36 h), or heat treatments of food processing facilities, is a viable alternative to methyl bromide fumigation. The confused flour beetle, *Tribolium confusum* (Jacquelin du Val) (Coleoptera: Tenebrionidae), is a common pest in food processing facilities worldwide. The time-mortality relationships for *T. confusum* exposed to temperatures used during heat treatments is unknown. Information on temperature-time-mortality relationships is essential for optimizing insect control when conducting heat treatments, and for developing thermal death kinetic models for predicting insect mortality under field conditions.

Objectives

1. Determine the most heat tolerant life stage of *T. confusum*.
2. Explore a novel thermal death kinetic model for the most heat tolerant life stage of *T. confusum*
3. Validate the thermal death kinetic model using independent data collected during actual facility heat treatments

Materials and Methods

Determining the heat tolerant stage: Eggs (3-d old), young larvae (2-d old), old larvae (22-d old), pupae (27-d old), and adults (2-wk old) (Fig. 1), were exposed for varying time periods to 50, 54, 58 and 60ºC and 22-35% RH in plastic boxes (4.5x4.5x1.5 cm) with 1.5 g of whole wheat flour. At each temperature-time combination 100 insects were exposed. Each temperature-time combination was replicated three times. Time-mortality data for each stage and temperature were fit to the complementary log-log regression model to determine LT_{99} values. LT_{99} values of any two life stages at each temperature were compared using the ratio test (Robertson and Preisler 1992). If the ratio includes 1, then the two stages are significantly different ($P < 0.05$) from one another.

Thermal death kinetic model development: The classical thermal death kinetic models used for bacterial inactivation at any given temperature (Stumbo 1973) are unsuitable for describing logarithm of insect survival over time, because insect survival is nonlinear over time. Therefore, we described logarithm of survival of the most heat tolerant stage over time at 46-60ºC using two separate nonlinear regressions. The model parameters are given in Table 1. *D*, the time required for one log reduction in population size (larval survival), was calculated from the fitted nonlinear regressions using differential equations (Table 2), programmed in Microsoft Excel to calculate a mean instantaneous *D*. The nonlinear relationship between mean instantaneous *D* and temperature (*x*) was described by:

$$y = a + b\exp(-x/c) \qquad (1)$$

where, *a*, *b*, and *c* are parameters of the fitted model.

The thermal death kinetic model was derived from the following relationship:

$$\log_{10}\left(\frac{N_{t-dt}}{N_t}\right) = \frac{dt}{D(T_t)} \qquad (2)$$

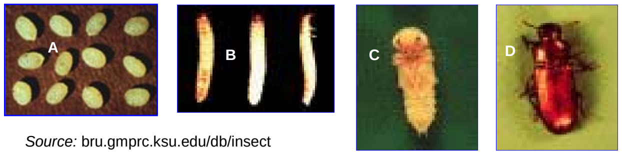
where, $N_{t\text{-}dt}$ is the survival at *t-dt* time interval and N_t is survival at time *t*. Upon integration equation (2) becomes:

$$\int_0^t \log_{10}\left(\frac{N_{t-dt}}{N_t}\right) = \int_0^t \frac{dt}{D(T_t)} \qquad (3)$$

$$\frac{N_0}{N_t} = \int_0^t \frac{dt}{D(T_t)} \qquad (4)$$

$$N_t = \frac{N_0}{\sum_0^t \frac{\Delta t}{D(T_t)}} \qquad (5)$$

where, N_o is the original number of insects, Δt is the incremental exposure time (0.5 minutes), *D* is the mean instantaneous *D*-value as a function of temperature (*T*), and T_t is the time-dependent temperature profile.



Source: bru.gmprc.ksu.edu/db/insect

Fig. 1. Eggs (A), larvae (B), pupa(C), and adult (D) of *T. confusum.*

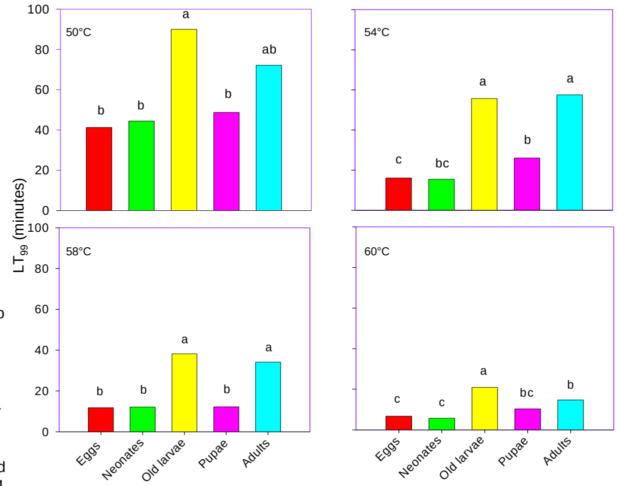


Fig. 2. Susceptibility of *T. confusum* life stages at 50 to 60°C. At each temperature, bars with different letters are significantly different ($P < 0.05$).

Table 1. Parameters of the nonlinear equations describing the relationship between logarithm of larval survival as a function of time.

Temp (ºC)	*a*	*b*	*c*	*d*	Adj R^2
46	1.95	-5.78	296.58	31.55	0.99
50	1.97	-0.01	-0.02		0.94
54	1.99	-0.01	-0.04		0.95
58	1.99	-0.03	-0.06		0.96
60	1.97	-0.04	-0.10		0.95

Table 2. Differential equations used for calculating instantaneous *D*-values from the nonlinear relationship between logarithm of insect survival and time of exposure.

Temp (ºC)	N	Differential equation (*dy*/*dx*)[a]	Mean *D(T)* (min)
46	18	$-b/(1+\exp(-(x-c)/d))^2 * -1/d*\exp(-(x-c)/d)$	881.6
50	22	$((1+bx)*c - (a+cx)*b)/(1+bx)^2$	83.8
54	18	$((1+bx)*c - (a+cx)*b)/(1+bx)^2$	34.4
58	12	$((1+bx)*c - (a+cx)*b)/(1+bx)^2$	42.0
60	11	$((1+bx)*c - (a+cx)*b)/(1+bx)^2$	26.8

[a]The nonlinear equation at 46ºC was $y = a+b/1+\exp(-(x-c)/d)$, and at 50-60ºC was $y = a+cx/1+bx$.

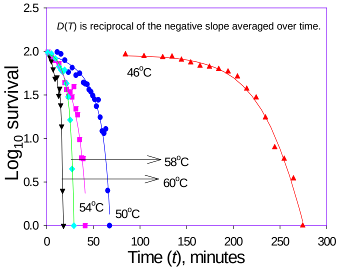


Fig. 3. Nonlinear relationship between survival of old larvae and time of exposure at 46-60ºC.

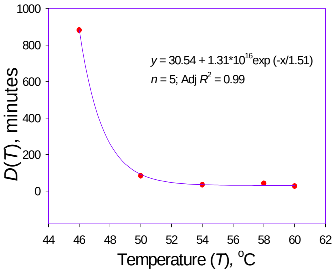


Fig. 4. Nonlinear relationship between mean *D*(*T*) and temperature.

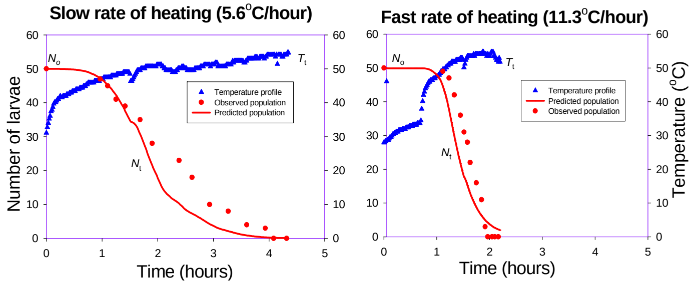


Fig. 5. Observed and predicted survival of old larvae of *T. confusum* at slow and fast heating rates recorded during heat treatment of the Kansas State University pilot feed mill, 5-7 August 2003.

Model validation: The temperature during a facility heat treatment was collected using HOBO® data loggers (Onset Computer Corp., Bourne, MA) at two locations in the Kansas State University during 5-7 August 2003 heat treatment. At each location, 14 plastic boxes each with 50 old larvae were removed at 14 different time intervals and observed for mortality. Larval survival was calculated as: 50 - number of dead larvae. The temperature data at the two locations were used to predict larval survival using equation 5. Absolute deviation from model predictions, both in terms of larval survival and time taken for equal survival, was determined from the graphs.

Results

The susceptibility of old larvae was similar to that of adults at 50, 54, and 58°C. In general, old larvae had the highest LT_{99} value at 50-60ºC (Fig. 2). Eggs, young larvae, and pupae were more susceptible than old larvae at the temperatures tested. The relationship between logarithm of larval survival and time was nonlinear (Fig. 3). The relationship between instantaneous *D* and temperature was also nonlinear (Fig. 4). The old larvae were sampled within 5 h of the total 24 h heat treatment. The slow heating rate lasted 261 minutes and was 5.6ºC/h and the fast heating rate lasted 131 minutes and was 11.3ºC/h (Fig. 5) The predicted larval survival was close to the observed values at the beginning and end of the heat treatment, and less than the observed survival during the intermediate phase of the heat treatment. The absolute deviation from model predictions in larval survival throughout the heat treatment at the slow and fast rate of heating was 3.7 and 6.8 insects per 50 insects, respectively. Similarly, the absolute deviation in time to equal larval survival at slow and fast heating rates was 17.3 minutes and 14.4 minutes, respectively.

Conclusions

The novel thermal death kinetic model was within 7-14% with respect to the number of larvae surviving following heat treatment and within 7-11% with respect to time for equal larval survival. This new model appears to be appropriate for describing survival of insect pests exposed to elevated temperatures. Further modifications in the increments used to calculate instantaneous *D*-values and use of a correction factor in predicting larval survival are being investigated to improve model predictions.

References

Robertson, J. L., and H. K. Preisler. 1992. Pesticide bioassays with arthropods. CRC Press, Boca Raton, FL.
Stumbo, C.R.. 1973. Thermo bacteriology in Food Processing. Academic Press Inc., New York.

Acknowledgments: We thank Temp-Air® (Burnsville, MN) for conducting the feed mill heat treatment. Research reported here was funded by CSREES-USDA (RAMP) under Agreement No. 00-51101-9674, and in part, by USDA-MAFMA.