Development and comparison of two models to predict survival rates of young larvae of *Stegobium paniceum* (L.) (Coleoptera: Anobiidae) under heat treated temperatures

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Abstract

Predicting mortality or survival rate of insects at heat treatment temperatures is critical for commercial heat treatment of food and storage facilities. Two models were developed to predict the survival rate of young larvae of drugstore beetle, *Stegobium paniceum* (L.) (Coleoptera: Anobiidae) under steady state or transient temperature condition: modified fundamental kinetic model and modified complementary log-log transformation model. Published young larvae mortalities and raw data of the temperature history, determined at different heat treatment temperatures, were used to develop these models. The models were verified and compared by using the field data collected in a medium sized mill. Both of the developed models overestimated the insect mortality in the mill when temperature was >53°C and underestimated insect mortality when temperature was <50°C. The lowest mean of the absolute difference between the predicted and measured insect mortality in the mill was 16.7±1.1% which was generated by using the modified complementary log-log transformation model. The possible reason of this divergence from the model is discussed.

Keywords: *Stegobium paniceum* (L.), Survival, Heat treatments, Modeling.

1. Introduction

Managing stored-product insects by heating food processing and storage facilities to lethal temperatures is an old and effective technology (Dean, 1913). There is renewed interest in using this old technology (Beckett et al., 1998; Mahroof et al., 2003) due to the desire to develop alternatives to the current systems of grain preservation and pest control. A heat treatment consists of heating all or part of a facility to 50–60°C and maintaining the temperature for 24–36 h (Mahroof et al., 2003; Tang et al., 2007). This method is used in facilities constructed with a wide variety of materials, brick, concrete, stone, and wood with metal sheathing, but structural damage sometimes might be a risk (Dowdy and Fields, 2002; Beckett et al., 2007). Although modern building construction can tolerate temperatures in excess of 50°C, some of the equipment in food processing and storage facilities cannot. If the temperature requirements necessary for effective control could be reduced, costs can be reduced. Therefore, predicting survival rate of insects under heat treatments would make this alternative to methyl bromide more widely used.

To systematically develop and assess heat treatments, models have been developed to predict survival insects under heat treatment temperatures. Models in the literature describing the thermal death kinetic data of insects range from fundamental kinetic models to semi- or purely- empirical models (Wang et al., 2007). The common characteristic of these published models was that it used one mathematical equation to describe the relationship between insect mortality and time at a given temperature. This assumption is usually developed based on the laboratory observation under constant temperatures. Therefore, it is usually scaled back to predict insect mortality at constant temperatures. Some developed models, such as fundamental kinetic model and complementary log-log transformation, could not be used to calculate insect mortality at transient temperature condition. Based on the logarithmic model, Boina et al., (2008) developed a dynamic model and this model could be used to predict insect mortality under transient temperature.

The fundamental kinetic model (Wang et al., 2002a, b; Gazit et al., 2004; Johnson et al., 2003 and 2004; Hallman et al., 2005) and complementary log-log transformation model (Jones et al., 1995; Thomas and Mangan, 1997; Waddel et al., 1997) have been successfully used to predict insect mortality at constant temperature. It is not known if its basic assumption could be used to develop a model to predict insect mortality under transient temperatures.

Selection of the appropriate model depends on research preferences, intended use, target insects, and temperature range (Wang et al., 2007). These multiple choices make the model selection and using part art and part science. An ideal mathematical model for the prediction of insect mortality under heat treatment should be developed based on experimental data and be used in heat treatment with certain accuracy. It should be usable for different insects under different treatment conditions. Model comparison of the developed models by using the same laboratory and field data might be an effective tool to find the ideal and robust model.

Stegobium paniceum (L.) (Coleoptera: Anobiidae) is one of the most common insects found in botanicals warehouses (Awadallah et al., 1990; Arbogast et al., 2002; Abdelghany et al., 2009a, b). It has been recorded from wide range of food, but its distribution is more temperate than tropical (Lefkovitch and Currie, 1967). Young larvae are more heat tolerant than the other stages (Abdelghany et al., 2009b). Therefore, heat treatments that results in a 100% mortality of young larvae should control all other stages of *S. paniceum*.

The aim of this study was to: 1) develop the following two models (by using the same laboratory data) which could predict the mortality of young larvae of *S. paniceum* under steady state or transient temperature conditions: modified fundamental kinetic model, and modified complementary log-log transformation; 2) validate and verify the developed models by using the same field data; and 3) compare the developed models.

2. Data used in the development and verification of the models

During model development and model calibration, the raw and published data related to the young larvae of *S. paniceum* published by Abdelghany et al., (2009b) were used, except specified otherwise. In the laboratory, the time-mortality relationships of the young larvae were determined at constant temperatures of 42, 45, 50, 55 and 60^{0}C and at different treatment times. The temperature rose to the target temperature within 30 min and once the target temperature was obtained it remained stable.

To verify the developed models, comparison between the predicted and measured insect mortalities was conducted. The measured insect mortality included the data collected in both the laboratory and field. The laboratory data were the same as that used in the model developments and calibrations. Field data was collected in Western Canada at a medium sized mill from Oct 23 and 24, 2008.

3. Data collection in mill

The young larvae were prepared at the room temperature in the laboratory of Cereal Research Center, Agriculture and Agri-Food Canada, Winnipeg (Abdelghany et al., 2009b). Wheat flour (10 g at about 12% moisture content, wet basis) mixed with brewer yeast (95:5 by weight) was loaded into vials (3 cm diameter, 5 cm high). Vials were covered with 600-µm wire mesh after the 50 young larvae were introduced at the top of the flour. The vials with insects were shipped to the mill and there were three days between the insect introduction and the beginning of the heat treatment. During shipment, the larvae experienced the temperatures from 20 to 30°C.

Seven vials, each containing a different species (other species presented in Hulasare et al., 2010), were grouped together around a Hobo data logger (Onset Computer Corp. Bourne, MA). There were 13 sets of vials placed in a 20 cm diameter circle on the concrete floor. At the middle of the ring, there was one set of vials with the same amount flour and yeast, but without insects. The temperatures inside these vials at the middle of the ring were measured by introducing T-type thermocouples connected with Hobo data logger, with temperatures recorded every 1 min. The thermocouples were located at the center of the flour inside each vial. During heating treatment, the floor temperature was also measured with hand held thermocouples (52 Thermometer, John Fluke MFG) taped to the floor and readings taken every 30 min. The thermocouples were calibrated within ±0.1°C using a mercury thermometer.

The mill was heat treated from 9:15 am to the next day 10:00 am. The temperatures took 9 h to rise maximum temperature of 58°C at the floor. The heating rate was about 3.8°C/h. During that period, groups of the vials were taken out of the mill when the vial temperatures were approximately 40, 42, 45, 47, 50, 52, 55, and 60°C. The heat-treated young larvae were shipped back and held in the laboratory at 30°C, 70% r.h.. until the emergence of adults. The criterion for survival was emergence to adults.

Insect mortality was calculated by using Abbott's equation (Abbott, 1925) and control was at 40°C. Four replications were conducted in the heat treated mill. However, three replicates had a higher than 42% control mortality (possible reason being the long distance of shipment, mortality during sample preparation, or problems with the initial rearing). Therefore, only one replicate with control mortality at 20% was used to verify the model.

The temperature inside the vials was higher than the temperature on the floor. The relationship between these two temperatures in the temperature range from 40 to 60°C was:

$$T_{floor} = -6.8 + 1.1T_{vial} \qquad R^2 = 0.96 \qquad (1)$$

where, T_{floor} and T_{vial} are the temperatures on the floor and inside the vial, respectively.

It was assumed that some young larvae might be at the bottom of the vials due to larvae seeking cooler temperatures during the heat treatment in the mill. Some insects at the bottom of the vials might experience different temperatures as those insects at the top or middle of the vial. Therefore, both the vial and calculated floor temperatures were used to predict the insect mortality.

4. Development of the models

4.1. Modified fundamental kinetic model (FKM)

The method used in the development of the fundamental kinetic model was the same as described by Wang et al., (2007). It was found: 1) the 0 –order model (Eq. 2) was the best fitted equation with an average determination coefficient (R^2) = 0.85 and minimum = 0.72 (which was at 50°C); 2) K value in the 0-order model followed the Arrhenius relationship (Eq. 3); and 3) C value in the 0-order model was close to 1.0.

$$S = -Kt_c + C \qquad (2)$$

$$log_{10}^{K} = log_{10}^{K_{ref}} - \frac{E_a}{R}\left(\frac{1}{T_{t_c}} - \frac{1}{T_{ref}}\right) \qquad (3)$$

where; S is the insect survival rate at a constant temperature and in t_c (min) is the treatment time; C is a constant at each constant temperature; K is the rate constant (min^{-1}) at a constant temperature; K_{ref} is the reaction rate constant at the reference temperature T_{ref} =314.35K (41.2°C) (Table 1); T_{t_c} is the temperature as a function of chronological time (t_c); E_a is the activation energy (J/mol) (Table 1); and R is the universal gas constant (8.314 J/mol.K).

Table 1 Value of the parameters in Eq. 3.

Parameter	Mean±SE	P
$log_{10}^{K_{ref}}$	-3.5042±0.2063	0.0004
E_a	136483.3825±17015.8166	0.0040

The C values could be calculated by using the following regressed Lorenzian equation:

$$C = 1.1475 - \frac{0.3057}{1+\left(\frac{T_{t_c}-52.6263}{5.7746}\right)^2} \qquad R^2 = 0.93 \qquad (4)$$

The Eq. 2 could not be used to calculate the insect survival rate at transient temperatures. Therefore, the following assumption was made: 1) C = 1; and 2) K was only influenced by temperature. The reason for the first assumption was: 1) C values remain constant at around 1.0 for several studied insects (Stumbo, 1973; Gazit et al., 2004; Wang et al., 2007); and 2) the calculated average C value was ≈ 0.9940 when Eq. 4 and filed temperature data was used. Eq. 2 was re-written as:

$$1 - S = Kt_c \qquad (5)$$

Eq. 5 was written in a differential form as following:

$$1-\frac{dN_{t_c}}{N_0}=K(T_{t_c})dt_c \qquad (6)$$

where; dN_{t_c} is the insect survival in a small time period of t_c; N_0 is the initial number of insects; $K(T_{t_c})$ is K as show in Eq. 2, 3 and 5 in the small time period of t_c and it is function of T_{t_c}; and dt_c is the small time period of t_c and in differential form.After integration of both sides of Eq. 6 and conversion of the mathematical equation to a numerical equation, Eq. 6 becomes:

$$M=\sum_{0}^{t_c}K\left(T_{t_c}\right)\Delta t_c \qquad (7)$$

where; M is the accumulated mortality from time 0 to t_c; and Δt_c is the incremental exposure time. At a constant temperature, Eq. 7 could be reduced to Eq. 5. During the model verification by using the field data, $K(T_{t_c})$ value was calculated by using Eq. 3; the T_{t_c} was the temperature at each time period; and $\Delta t_c = 1$ min.

4.2. Modified complementary log-log transformation model (CLLT)

The relationship between insect mortality and time at a given temperature was assumed as (Jones et al., 1995; Thomas and Mangan, 1997; Waddell et al., 1997):

$$M=1-e^{-e^{Kt_c+C}} \qquad (8)$$

where; K and C are constant at each constant temperature. Eq. 8 yielded the following equation after taking logarithms for two times:

$$Ln(-Ln(1-M))=-Kt_c+C \qquad (9)$$

It was found Eq. 8 fitted the insect mortality data with an average R^2 =0.93±0.04 and minimum = 0.80 (Table 2). Therefore, Eq. 8 was used to find the K and C value at each constant temperature by regression. To predict the K and C values at other temperatures (at which insect mortality was not determined in the laboratory), the found K and C values were used to conduct non-linear regression with K or C value as the dependent variable and temperature as an independent variable. The following were the best equations found (Table 2):

Table 2 K and C value at different constant temperatures

Temperature (°C)	**K**		**C**		
	Eq.8 [a]	**Eq.10** [b]	**Eq.8** [a]	**Eq.11** [b]	**R^2, Eq. 8**[c]
42	0.0029 ± 0.0002	0.0023	-2.8375 ± 0.1570	2.8375	0.98
45	0.0041 ± 0.0005	0.0046	-3.1936 ± 0.3367	3.1936	0.93
50	0.0127 ± 0.0025	0.0126	-1.7407 ± 0.3273	1.7407	0.80
55	0.8932 ± 1.7613	0.8857	-8.0975 ± 7.6124	8.1026	0.99
60	0.8783 ± 0.1762	0.8857	-3.1196 ± 0.7161	2.7877	0.96

[a] The K or C value (mean ± SE) regressed by using Eq. 8. All the $p < 0.0001$. [b] The K or C value calculated by using Eq. 10 and 11, respectively.[c] R^2 value regressed by using Eq. 8.

$$\begin{cases} k = \dfrac{0.7765}{1 + e^{-\frac{T_{t_c} - 47.4806}{4.7844}}} & 41.2°C < T_{t_c} < 50°C \quad R^2 = 0.98 \\ k = 0.0035 + \dfrac{0.8822}{1 + e^{-\frac{T_{t_c} - 48.8874}{0.1126}}} & T_{t_c} \geq 50°C \quad R^2 = 0.99 \end{cases} \tag{10}$$

$$\begin{cases} C = 5.2338 e^{-0.5\left(\frac{T_{t_c} - 44.2920}{4.6604}\right)^2} & 41.2°C < T_{t_c} < 50°C \quad R^2 = 0.98 \\ C = 2.7377 + 76.096 e^{-0.5\left(\frac{T_{t_c} - 54.4018}{0.2912}\right)^2} & T_{t_c} \geq 50°C \quad R^2 = 0.96 \end{cases} \tag{11}$$

To calculate the insect mortality at transient temperature, the following assumption was made: 1) C and K were only influenced by temperature; 2) Eq. 9 could be written in a differential form as follows:

$$Ln\left(-Ln\left(\frac{dN_{t_c}}{N_0}\right)\right) = -K\left(T_{t_c}\right)dt_c + C\left(T_{t_c}\right) \tag{12}$$

Where; $C\left(T_{t_c}\right)$ is C as show in Eq. 8, 9 and 11 in the small time period of t_c and is a function of T_{t_c}. After integration and mathematical conversion, Eq. 12 yields:

$$Ln\left(-Ln\left(\frac{dN_{t_c}}{N_0}\right)\right) = C\left(T_{t_c}\right) - \sum_0^{t_c} K\left(T_{t_c}\right)\Delta t_c \tag{13}$$

$$\sum_0^{t_c} M = 1 - e^{-e^{C(T_{t_c}) + \sum_0^{t_c} K(T_{t_c})\Delta t_c}} \tag{14}$$

At a constant temperature, Eq. 14 could be reduced to Eq. 9.

During the model verification by using the field data, the value of $K\left(T_{t_c}\right)$ and $C\left(T_{t_c}\right)$ were calculated by using Eq. 10 and 11, respectively; the T_{t_c} was the temperature at each time period; and $\Delta t_c = 1$ min.

5. Results and discussion

The modified fundamental kinetic model could predict the insect mortality at constant temperature of 50 and 55°C (Fig. 1 and 2). It underestimated insect mortality at 42 and 60°C (Fig. 1, and 2), and overestimated insect mortality at 45°C (Fig. 1). The modified complementary log-log transformation model could predict insect mortality at constant temperature of 45, 50, 55, and 60°C (Fig. 1 and 2). It underestimated insect mortality at 42°C (Fig. 1).

To compare the performance of the developed models at each constant temperature, the absolute difference between the insect mortalities measured and the predicted was calculated. The mean of the absolute difference calculated from the modified fundamental model was 18.6 ± 1.8% with a maximum 65%. The mean of the absolute difference calculated from the modified complementary log-log transformation model was 9.4 ± 1.0% with a maximum 53.8%. The paired t-test was conducted between the absolute differences of two developed models with t= 5.7916 and p<0.0001. The prediction accuracy of the modified complementary log-log transformation model was significantly higher than that of the modified fundamental model.

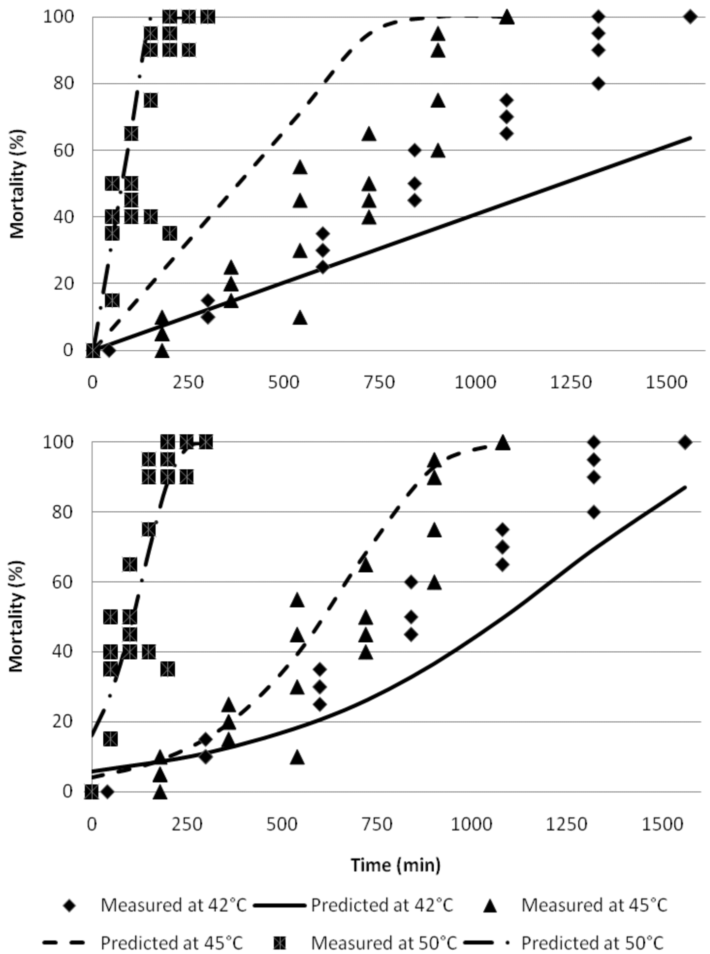

Figure 1 Insect mortality measured and predicted by using the following models at target temperature 42, 45, and 50°C: modified fundamental kinetic model (Top) and modified complementary Log-Log transformation model (Bottom).

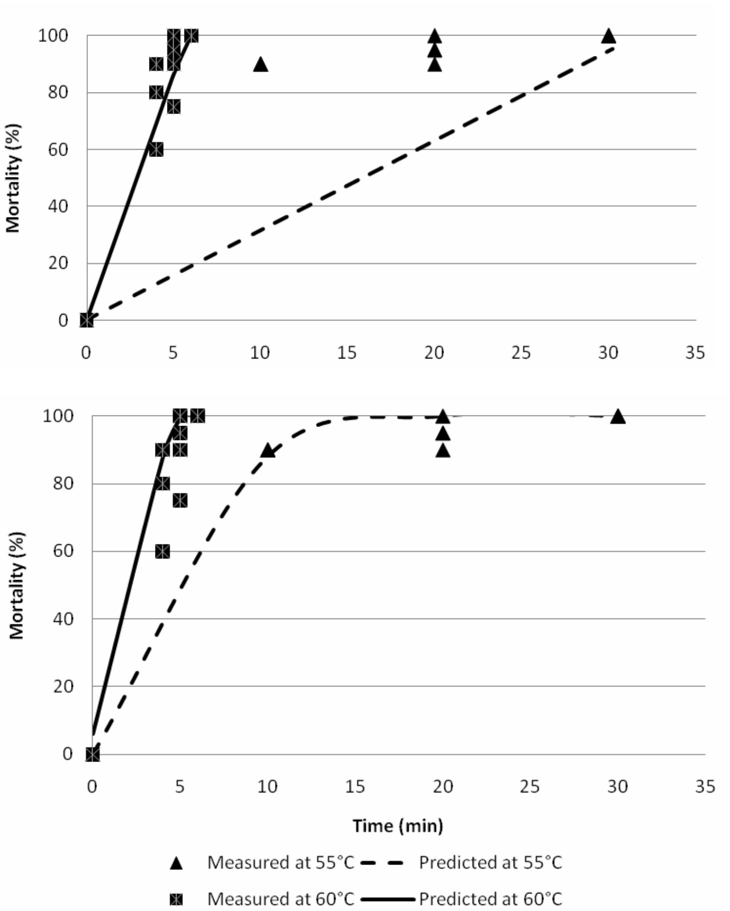

Figure 2 Insect mortality measured and predicted by using the following models at target temperature 55, and 60°C: modified fundamental kinetic model (Top) and modified complementary Log-Log transformation model (Bottom).

Both of the developed two models overestimated the insect mortality in the mill when temperature >53°C and underestimated insect mortality when temperature <50°C (Fig. 3). Using floor temperature increased the prediction accuracy (Fig. 3). This indicated that the insects in the vial might migrate to the bottom of the vial during heat treatment in the mil. The statistic result of the absolute difference between the predicted and measured insect mortality in the mill showed that (Table 3): when the floor temperature (T_{floor}) was used, the CLLT model had a better prediction; while the FKM had a better prediction when T_{vial} was used. However, both models had the same prediction trend (Fig. 3) and there was no significant different (SAS, 2008) between the predictions (Table 4), even though the modified complementary log-log transformation model had a better performance to predict insect mortality at each tested constant temperature.

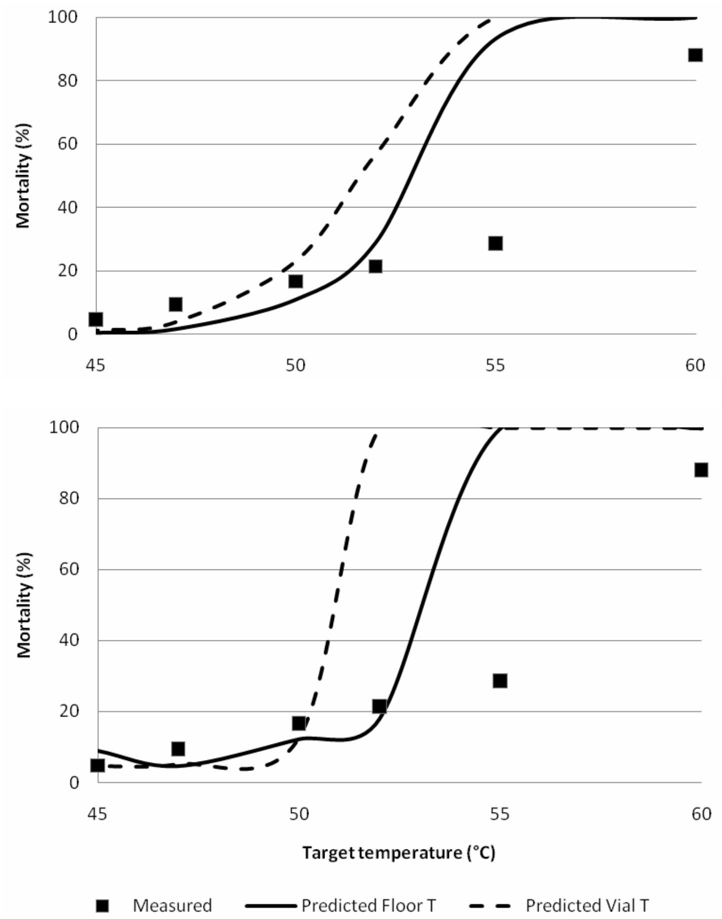

Figure 3 Insect mortality measured and predicted by using the following models in the heat treated mill: modified fundamental kinetic model (Top) and modified complementary Log-Log transformation model (Bottom). In the graph, 'Predicted Floor T' means the predicted insect mortality based on the calculated floor temperature; and 'Predicted Vial T' means the predicted insect mortality based on the measured vial temperature.

Table 3 Statistic of the absolute difference between the predicted and measured insect mortality in the mill

Statistic of the absolute difference	Predicted by using T_{floor}		Predicted by using T_{vial}	
	FKM	CLLT	FKM	CLLT
Mean ± SE	17.0 ± 9.6	16.7 ± 11.0	22.4 ± 10.9	28.4 ± 14.8
Maximum	64.7	71.4	71.4	78.6
Minimum	4.4	3.4	3.6	0.26

Table 4 Results of the paired t test between the absolute differences between measured and predicted insect mortality calculated from developed models by using the tested constant temperature, floor temperature in the mill, and the vial temperature

	t	P
Constant temperature	5.7916	<0.0001
T_{floor}	0.2068	0.8443
T_{vial}	-0.8148	0.4522

Both of the developed models: 1) underestimated the insect mortality determined at constant temperature of 42°C and when temperature <50°C in the mill; and 2) overestimated the insect mortality when temperature >53°C in the mill. These facts indicated that these two developed models worked better when treatment temperature was about 50°C. The reason for the overestimation or underestimation at other temperatures might be that these two models did not count the following factors: 1) heating rates (Beckett et al., 1998); 2) death effect during heating period (the time from room temperature to lethal temperature); 3) individual death time distribution; 4) different physiological deaths during heat treatment; and 4) enzyme complexes causing insect death. These un-accounted factors play important role in the insect death time during heat treatment (Tang et al., 2007). For example, the temperatures rose to 60°C within 15 min at laboratory condition or 10 min at 55°C will result 90% mortality of young larva of *S. paniceum* (Abdelghany et al., 2009b). Therefore, these two models could be used to predict mortality of insects when subjected to steady-state isothermal heating, and might have limitation when used at transient and non-isothermal conditions.

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