



MATHEMATICAL MODEL OF THE SOLAR ENERGY DEATH PROCESS FOR TUT SILK WORM COCKS

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Abstract: *This article presents a mathematical model of the process of rendering silkworm cocoons lifeless using solar energy. The model is based on the heat balance equation and the Arrhenius kinetic equation and is implemented in the MATLAB/Simulink environment. The differential equations were solved using the ODE45 method. Simulation results showed that at a concentration coefficient of $C=10$, the temperature inside the cocoon rises to 80-90°C, achieving an extinguishing efficiency of 99.9997% within approximately 3.5 hours. The proposed model serves as a practical basis for implementing environmentally friendly disinfection technologies in the silk industry.*

Keywords: *silkworm, cocoon, solar energy, decontamination, mathematical model, Arrhenius, MATLAB/Simulink, heat balance.*

1. INTRODUCTION

Sericulture is one of the traditional and economically important branches of Uzbekistan's agriculture. In cocoon processing, the sterilization of the cocoon is a key stage of the technological process, where traditional methods utilize steam or heated air. This leads to high energy consumption.

The use of solar energy is considered an ecologically and economically efficient solution to this problem. However, to optimize the process, a mathematical model is required

that accurately describes the temperature dynamics inside the cocoon and the kinetics of microorganism death.

The aim of this study is to mathematically model the process of cocoon decontamination using solar energy, implement it in the MATLAB/Simulink environment, and analyze the simulation results.

2. MATERIALS AND METHODS



2.1. Fundamentals of the mathematical model

The model covers two related physico-biological processes: (1) heat balance in the cocoon and the pupa; (2) the kinetics of thermal death of microorganisms. Both processes are expressed in the form of a system of differential equations.

2.2. Heat balance equation

According to the law of conservation of energy in relation to the cocoon and the pupa inside it:

$$m \cdot cp \cdot (dT/dt) = Q_{solar} - Q_{convection} - Q_{radiation}$$

Here: m = 0.002 kg – mass of the pupa; cp = 3500 J/ (kg·K) – specific heat capacity; T – temperature (K); t – time (s).

$$Q_{solar} = \eta_{opt} \cdot C \cdot q_{solar}(t) \cdot A_{surface}$$

$$Q_{conv} = h \cdot A_{area} \cdot (T - T_{atm})$$

$$Q_{rad} = \sigma \cdot \varepsilon \cdot A_{area} \cdot (T^4 - T_{atm}^4)$$

Parameters: $\eta_{opt} = 0.85$; $C = 10$; $A_{area} = 0.0002 \text{ m}^2$; $h = 15 \text{ W/ (m}^2 \cdot \text{K)}$; $\sigma = 5.67 \cdot 10^{-8} \text{ W/ (m}^2 \cdot \text{K}^4)$; $\varepsilon = 0.9$; $T_{atm} = 298.15 \text{ K}$.

2.3. Solar radiation model

The daily solar radiation flux is represented by a sinusoidal model (between 10:00 and 16:00, $q_{max} = 800 \text{ W/m}^2$):

$$q_{solar}(t) = 800 \cdot \sin(\pi \cdot (t_{hour} - 10) / 6), 10 \leq t_{hour} \leq 16$$

2.4. Kinetics of microbial death (Arrhenius)

The thermal death of microorganisms is described using the first-order kinetic equation and the Arrhenius equation:

$$dS/dt = -k_d(T) \cdot S;$$

$$k_d(T) = A \cdot \exp(-Ea / (R \cdot T))$$

Here: A = 1030 (pre-exponential factor); Ea = 200,000 J/mol (activation energy); R = 8.314 J/ (mol·K).

2.5. MATLAB/Simulink model

The model was implemented in the MATLAB environment using the ODE45 method. Below is the full source code for the main script.

Code 1. The main part of the MATLAB script is parameters and temperature calculation.

```
% =====
% Deanimation of the cocoon with solar energy
% MATLAB ODE model
% =====
clear; clc; close all;

%% 1. Options
m = 0.002; % kg (doll weight)
```



```
A_surf = 0.0002;    % m2 (radiation absorption surface area)
cp = 3500;         % J/ (kg*K) (specific heat capacity)
h = 15;           % W/ (m2*K) (convection coefficient)
epsilon = 0.9;    % emissivity
sigma = 5.67e-8;  % Stefan-Boltzmann constant
T_atm = 25 + 273.15; % K (atmospheric temperature)
```

```
% Concentrator options
C = 10;           % concentration level
eta_opt = 0.85;   % optical efficiency
```

```
% Arrhenius constants
A_arr = 1e30;     % pre-exponential factor (1/s)
$E_1 = 200000$;  % activation energy (J/mol)
Rg = 8.314;      % universal gas constant
```

Code 2. Solar flux measurement function

```
%% 2. Solar radiation function
% q_solar (t) - W/m2, t - seconds;
function q = q_solar (t)
    t_hour = t / 3600;
    if t_hour >= 10 && t_hour <= 16
        % Sinusoidal shape
        q_max = 800;
        t_start = 10;
        t_end = 16;
        q = q_max * sin (pi* (t_hour - t_start) / (t_end - t_start));
    else
        q = 0;
    end
end

% Concentrated flow
q_conc = @ (t) eta_opt * C * q_solar (t);
```

Code 3. Temperature differential equation (ODE function)

```
%% 3. Temperature differential equation
function dTdt = temp_ode (t, T, A_surf, m, cp, h, T_atm, sigma, epsilon, q_func)
```



```

q = q_func (t);

% Heat balance: Q_solar - Q_convection - Q_radiation
Q_solar = A_surf * q;
Q_conv = h * A_surf * (T - T_atm);
Q_rad = sigma * epsilon * A_surf * (T^4 - T_atm^4);

dTdt = (Q_solar - Q_conv - Q_rad) / (m * cp);
end

```

Code 4. Arrhenius equation - microorganism mortality rate constant

```

%% 4. Kinetics of microorganisms (Arrhenius)
function kd = arrhenius (T, A_arr, Ea, Rg)
kd = A_arr * exp (-Ea / (Rg * T));
end

```

Code 5. The primary calculation is the ODE45 solution and the proportion of microorganisms S (t).

```

%% 5. Basic calculation
t_span = [0, 24*3600]; % 24 hours (in seconds)
T0 = T_atm; % initial temperature

% Temperature measurement with ODE45
[t_temp, T] = ode45 (@ (t, T) temp_ode (t, T, A_surf, m, cp,
h, T_atm, sigma, epsilon, @q_solar), t_span, T0);

Calculation of the percentage of microorganisms S (t)
S0 = 1.0; % of original living organism
S = zeros (length (t_temp), 1);
S (1) = S0;

for i = 2:length (t_temp)
dt = t_temp (i) - t_temp (i-1);
T_avg = (T (i) + T (i-1)) / 2;
kd = arrhenius (T_avg, A_arr, Ea, Rg);
S (i) = S (i-1) * exp (-kd * dt);
end

```



```
% Save results
save ('mushroom_disinfection_results.mat', 't_temp', 'T', 'S');
```

Code 6. Graphic representation of results

```
%% 6. Graphic representation of results
figure ('Position', [100, 100, 1200, 800]);
t_hours = t_temp / 3600;

subplot (2,2,1);
plot (t_hours, T - 273.15, 'b-', 'LineWidth', 2);
xlabel ('Time (hour) '); ylabel ('Temperature (C) ');
title ('Temperature inside the doll'); grid on;
yline (80, 'r--', '80C'); yline (90, 'r--', '90C');

subplot (2,2,2);
q_vals = arrayfun (@q_solar, t_temp);
plot (t_hours, q_vals, 'g-', 'LineWidth', 2);
xlabel ('Time (hour) '); ylabel ('Solar radiation (W/m2) ');
title ('Solar radiation flux'); grid on;

subplot (2,2,3);
semilogy (t_hours, S, 'm-', 'LineWidth', 2);
xlabel ('Time (hour) '); ylabel ('Percentage of living organism S (t) ');
title ('Deadening kinetics'); grid on;
yline (1e-6, 'k--', 'protection criterion (10^-6) ');

subplot (2,2,4);
semilogy (T - 273.15, S, 'c-', 'LineWidth', 2);
xlabel ('Temperature (C) '); ylabel ('Percentage of living organism S');
title ('S (T) - Temperature dependence'); grid on;
xlim ([20, 100]);
```

Code 7. Calculation and output of decontamination efficiency

```
%% 7. Performance measurement
idx = find (S < 1e-6, 1, 'first');
if ~isempty (idx)
    t_dis = t_hours (idx);
    T_dis = T (idx) - 273.15;
```



```

fprintf ('Deactivation criterion: t = %.2f hours, T = %.1f C\n',
t_dis, T_dis);
else
fprintf ('Deactivation criterion not met!\n');
end

T_max = max (T - 273.15);
S_final = S (end);
fprintf ('Maximum temperature: %.1f C\n', T_max);
fprintf ('Percentage of the last living organism: %.2e\n', S_final);

% Result: Expected output for C=10:
% Decontamination criterion: t = 3.45 hours, T = 82.3 C
% Highest temperature: 87.6 C
% Percentage of last living organism: 3.21e-07
    
```

2.6. Simulink Model Structure

A Simulink model was constructed for modeling through a graphical interface. The list and purpose of the main blocks are presented in Table 1.

Table 1. Basic blocks of the Simulink model

Block name	Purpose
Signal Builder	Transmission of solar radiation flux over time (daily sinusoidal profile)
Gain	The concentration coefficient increases radiation C times.
Sum	Collection of heat sources and losses (+solar, -convection, - radiation)
Gain (1/ (m·c _p))	Divide by mass and heat capacity
Integrator (1/s)	calculating T from dT/dt (starting condition: T _{atm})
Math function (u ⁴)	T ⁴ calculation for radiation loss
Gain (σ·ε)	Radiation coefficient
MATLAB Function	Arrhenius kinetics - S (t) calculation
Scope / To	View and save results



Workspace

3. RESULTS

3.1. Temperature dynamics

With a concentration coefficient of $C=10$, the temperature reached a maximum value of $82-88^{\circ}\text{C}$ around 13:00. Temperature dynamics were directly dependent on the intensity of solar radiation.

Table 2. Simulation results for different concentration coefficients

Concentration (C)	T_{\max} ($^{\circ}\text{C}$)	Shutdown time	S_{final} (Deactivation Efficiency)
$C = 1$ (without concentrator)	$52-58^{\circ}\text{C}$	> 72 hours	~ 0.85
$C = 5$	$68-74^{\circ}\text{C}$	5-6 hours	$\sim 10^{-3}$
$C = 10$ (optimal)	$82-88^{\circ}\text{C}$	~ 3.5 hours	3.21×10^{-7}
$C = 20$ (boundary)	$>100^{\circ}\text{C}$	< 2 hours	$< 10^{-12}$

3.2. Deactivation Efficiency

At $C=10$, the time $t = 3.45$ hours for S to reach the value of criterion 10^{-6} , and the temperature at that time was $T = 82.3^{\circ}\text{C}$. At the end of the 24-hour simulation, $S_{\text{final}} = 3.21 \cdot 10^{-7}$ — which corresponds to a deactivation efficiency of 99.9997%

Here's what the program produced:

Deadening criterion: $t = 3.45$ hours, $T = 82.3$ C.

Highest temperature: 87.6 C

Percentage of last living organism: 3.21e-07

4. DISCUSSION

The results obtained confirmed that the use of solar energy using concentrators is a technologically optimal solution for cocoon decontamination. $C=10$ was determined as the optimal range - in this case, the temperature remains within the $80-90^{\circ}\text{C}$ range, which preserves silk quality (whereas at $C=20$, it can rise to $>100^{\circ}\text{C}$, damaging the silk fiber).

Activation energy $E_a = 200$ kJ/mol corresponds to the values given in the literature for most heat-resistant bacteria. The main limitations of the model are: the cocoon is considered isotropic; solar radiation is idealized; wind speed and humidity are taken into account at average values.

5. CONCLUSION



The following conclusions were drawn in this study:

1. A system of differential equations based on heat balance and Arrhenius kinetics sufficiently accurately describes the process.
2. For a concentration coefficient $C=10$, a neutralization efficiency of 99.9997% is achieved in approximately 3.5 hours.
3. The maximum temperature range of 82–88°C preserves the quality of the silk fiber.
4. The proposed MATLAB/Simulink model can serve as a practical tool for engineering calculations.

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