3-Dimensional numerical modeling of radio frequency selective heating of insects in soybeans

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Overview

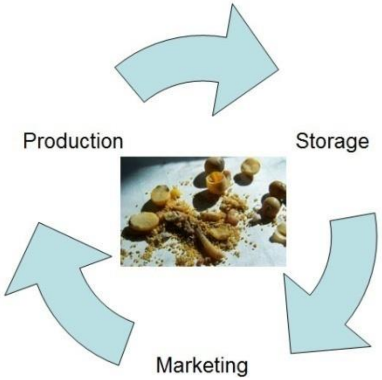
- Introduction
- Materials and methods
- Computer simulation
- Model validation
- Model applications

Introduction

- **Broad uses of soybean**

Human and animal food	Medical applications	Industrial applications

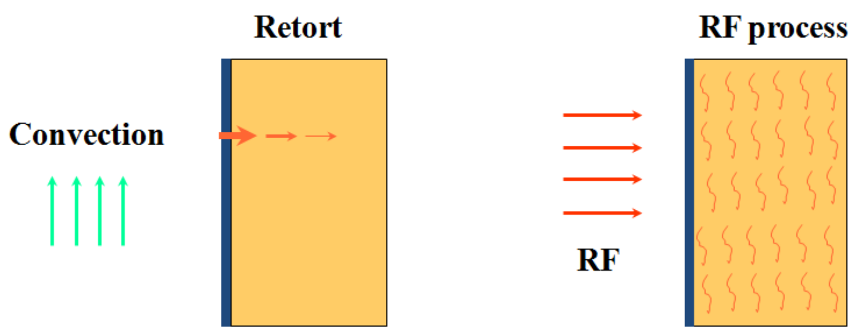
- **Infestation** by postharvest insect pests in soybeans

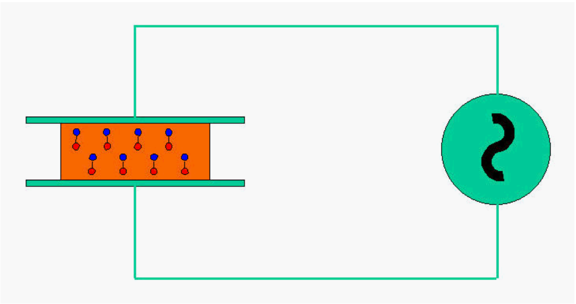


- Direct damage
  - Feeding, webbing production
- Indirect damage
  - Induction of diseases

Introduction

- **RF treatments** can provide **rapid** and **volumetric** heating for postharvest insect control in dried products
  - Volumetric heating -- the electromagnetic waves **directly couple** with material to generate heat
  - Rotational response of **polarized molecules** and **migration** of charged ions



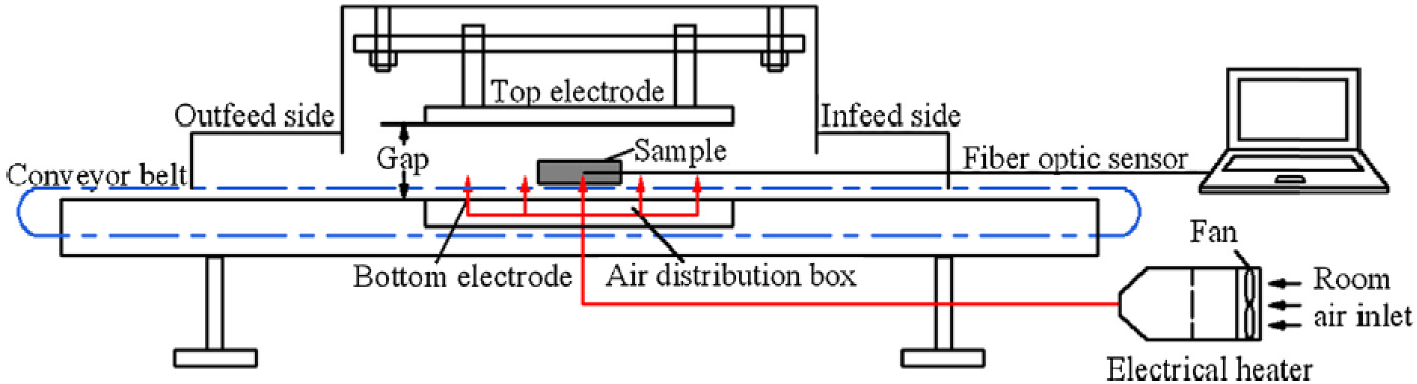


27 MHz = 27 Million times/second

  - **Non-chemical**, non-contact, environmentally friendly
  - **Selectivity**

Introduction

- Computer simulation is a very effective tool to help understand the complex RF dielectric heating process



- There are few reports on the finite element simulation to show the differential heating of insects in host soybeans when subjected to an electromagnetic field

Objectives

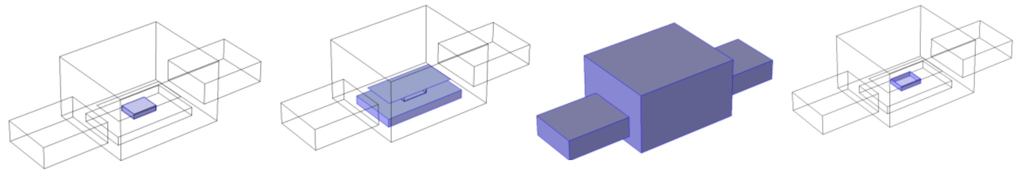
- Develop a computer **simulation model** for a 6 kW, 27.12 MHz RF system using commercial finite element software COMSOL Multiphysics

- **Validate the model** by comparing three-layer transient experimental temperature profiles in soybeans after 6 min RF heating

- Apply the validated model to predict the effects of **insect positions, orientations, dielectric properties, and sizes** on the behavior of differential RF heating between insects and soybeans

Materials and methods

Table 1. Electrical and thermo-physical properties of materials used for computer simulation



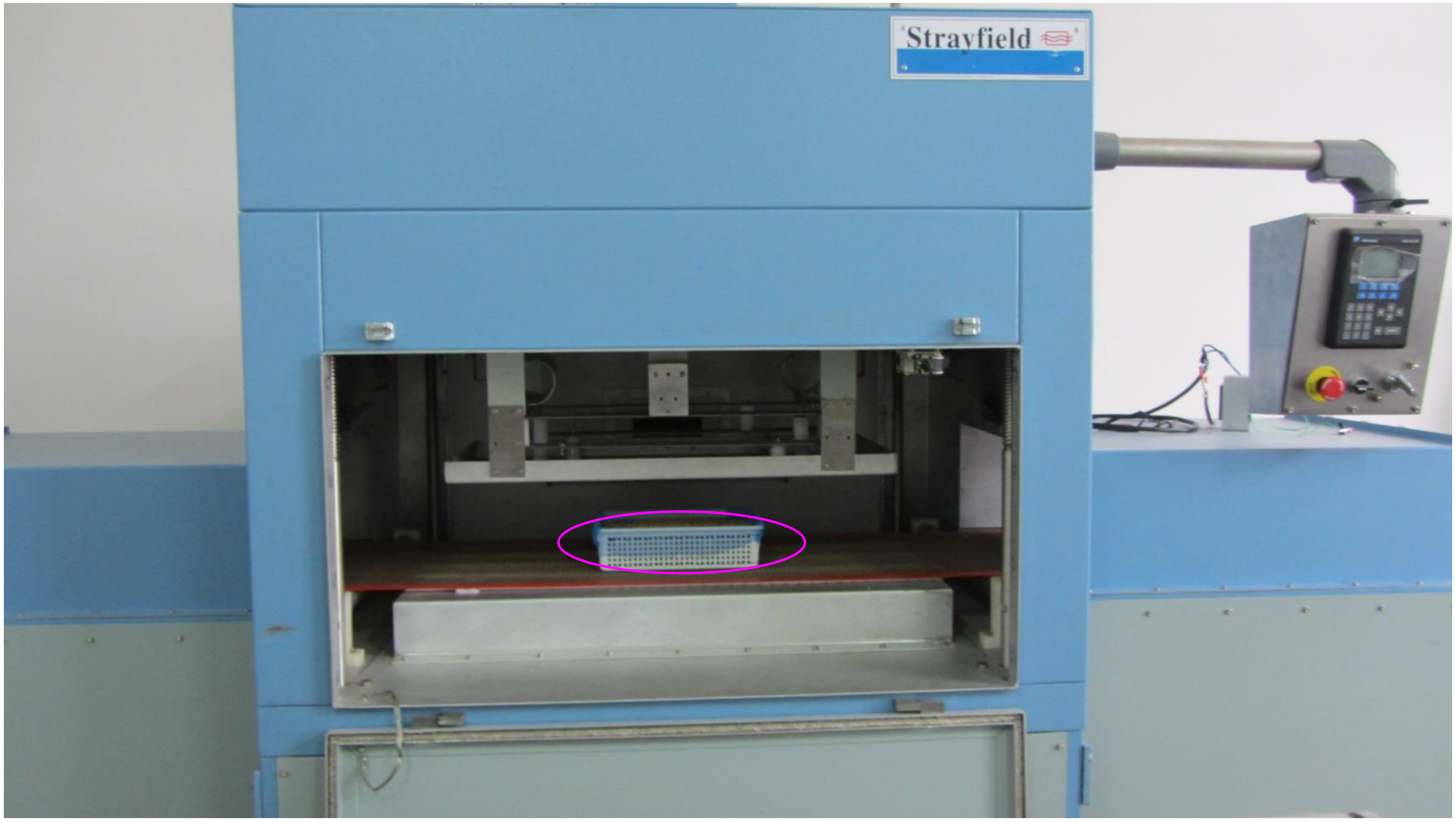
Material properties	Indianmeal moth	Dry soybeans	Aluminum	Air	Polypropylene
Density ρ (kg/m^3)	1008	739	2700	1.2	900
Thermal conductivity k (W/m °C)	0.51	0.11	160	0.025	0.26
Heat capacity c_p (J/kg °C)	3450	1829	900	1200	1800
Dielectric constant	0.81*T+63.12	0.048*T+0.81	1	1	2.0
Loss factor	4.42*T+109.86	0.007*T-0.05	0	0	0.0023

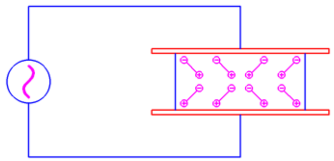
T-temperature (20°C $\le$ T $\le$ 60°C).

Moisture content: 6.18 ± 0.04% (w.b.) for soybeans, 74.0% (w.b.) for insect larvae

Computer simulation

- 6 kW, 27.12 MHz free-running oscillator RF heating system





➢ **Heat transfer**

Electric field intensity: $-\nabla \cdot \left(\left(\sigma + j2\pi\varepsilon_0\varepsilon' \right) \nabla V \right) = 0$

RF power conversion: $Q(x, y, z) = 2\pi f \varepsilon_0 \varepsilon'' \left| \vec{E} \right|^2 \quad \left| \vec{E} \right| = -\nabla V$

Boundary conditions: $-k\nabla T = h(T - T_a)$

➢ Heat transfer in **soybean samples :** $\rho_s c_{ps} (\frac{\partial T}{\partial t})_s = k_s (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) + Q_s(x, y, z, t)$

➢ Heat balance equation of **insect larvae:** $\rho_i c_{pi} V_i (\frac{\partial T}{\partial t})_i = k_i A_i (\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}) + Q_i(x, y, z, t) V_i$

➢ Electric field intensities in **the insect**: $E_i = E_s \left(\frac{3\varepsilon_s}{2\varepsilon_s + \varepsilon_i} \right)$

➢ **COMSOL Multiphysics V4.3a** **(Joule heating model)**

Computer simulation

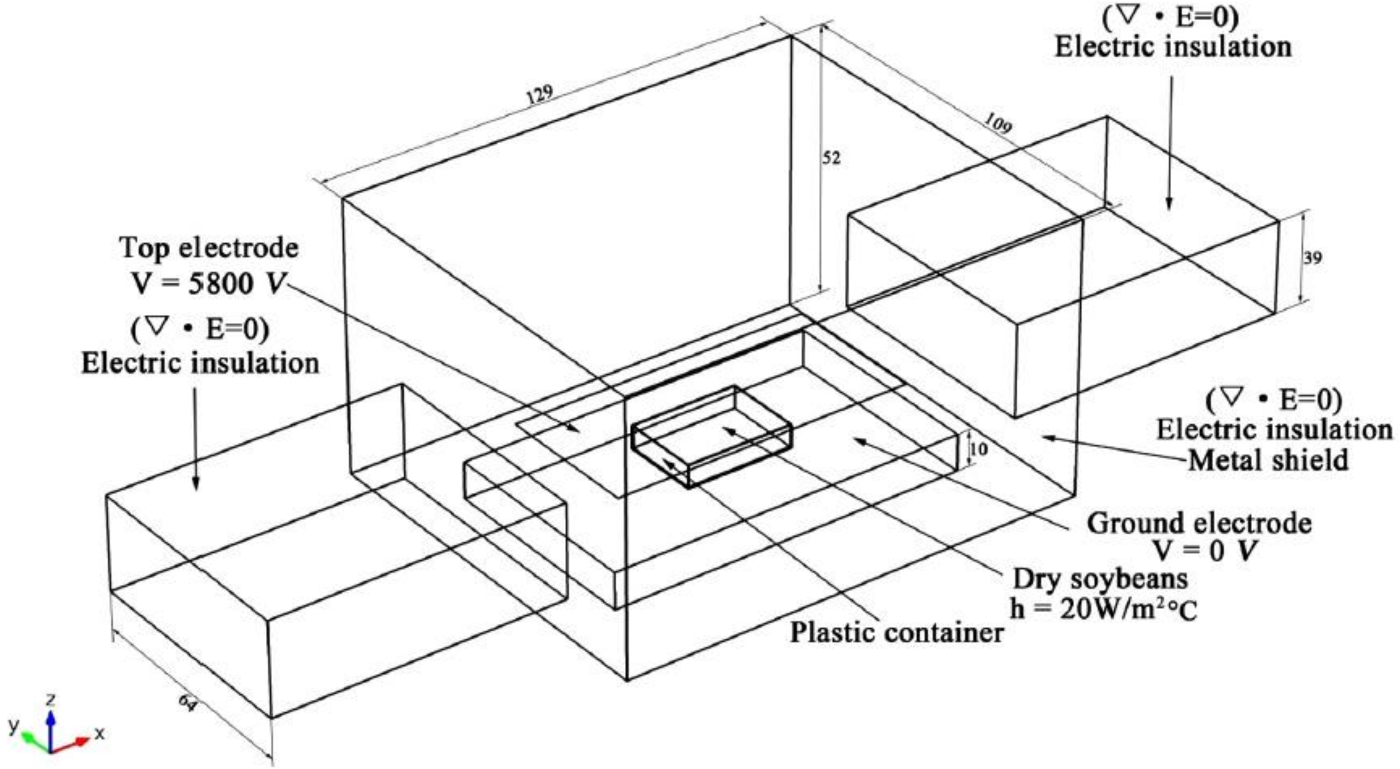
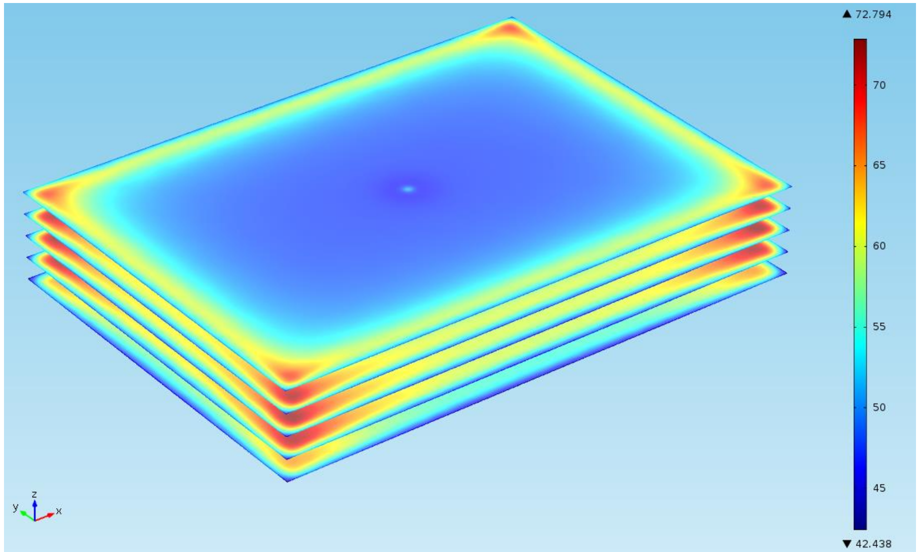
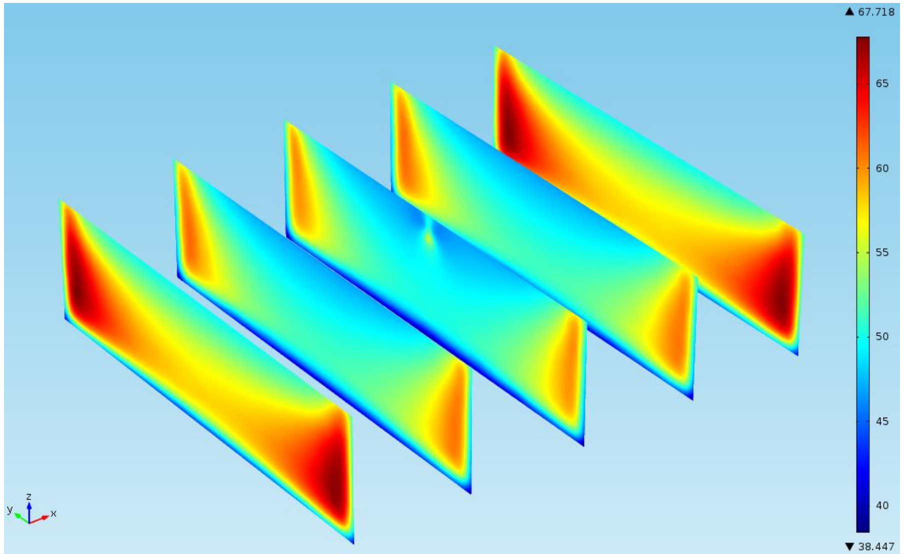
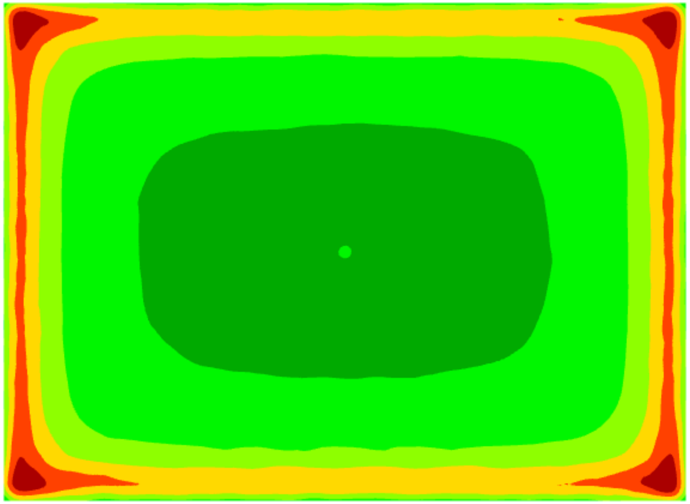


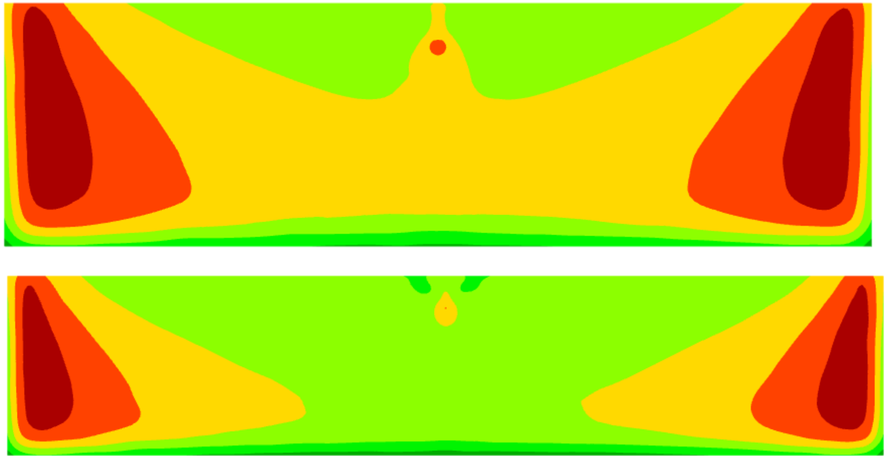
Fig. 1. Boundary and initial conditions for the RF system used in the computer simulation model (all dimensions are in cm).

Computer simulation









Model validation

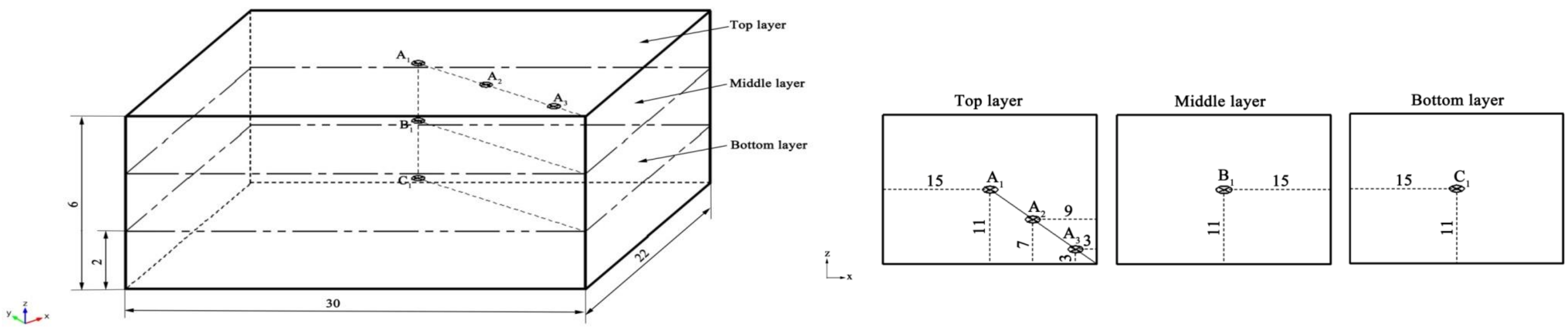


Fig. 3. Different positions of insects at the center part for each layer (A_1, B_1, and C_1) and three horizontal positions at the top surface layer (A_1, A_2, and A_3) after 6 min RF heating with insect body positioned vertically, electrode gap of 12 cm, and initial temperature of 25 °C (all dimensions are in cm).

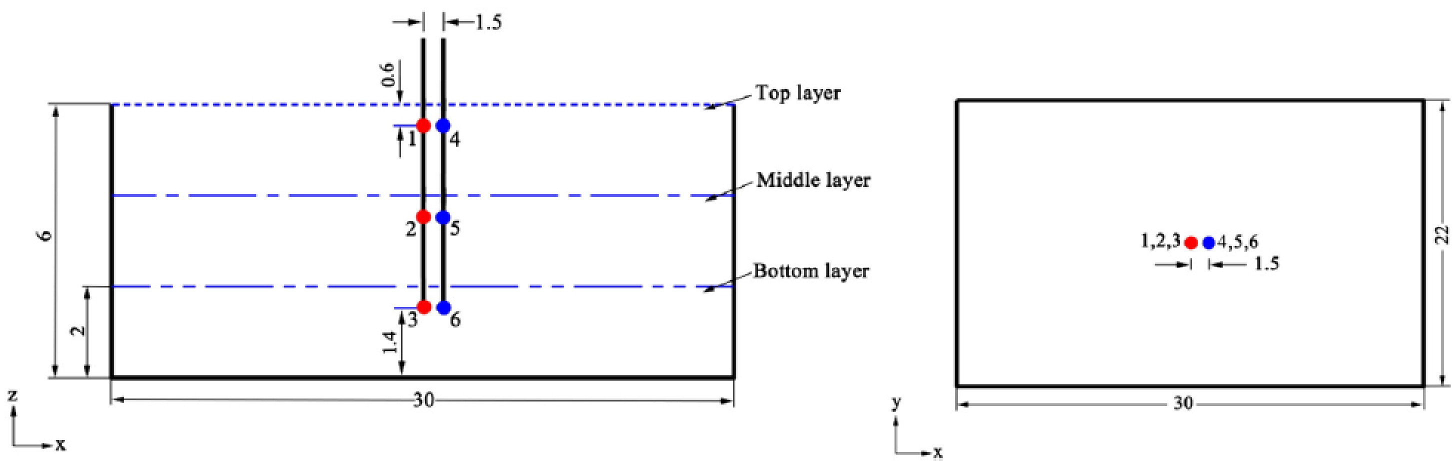
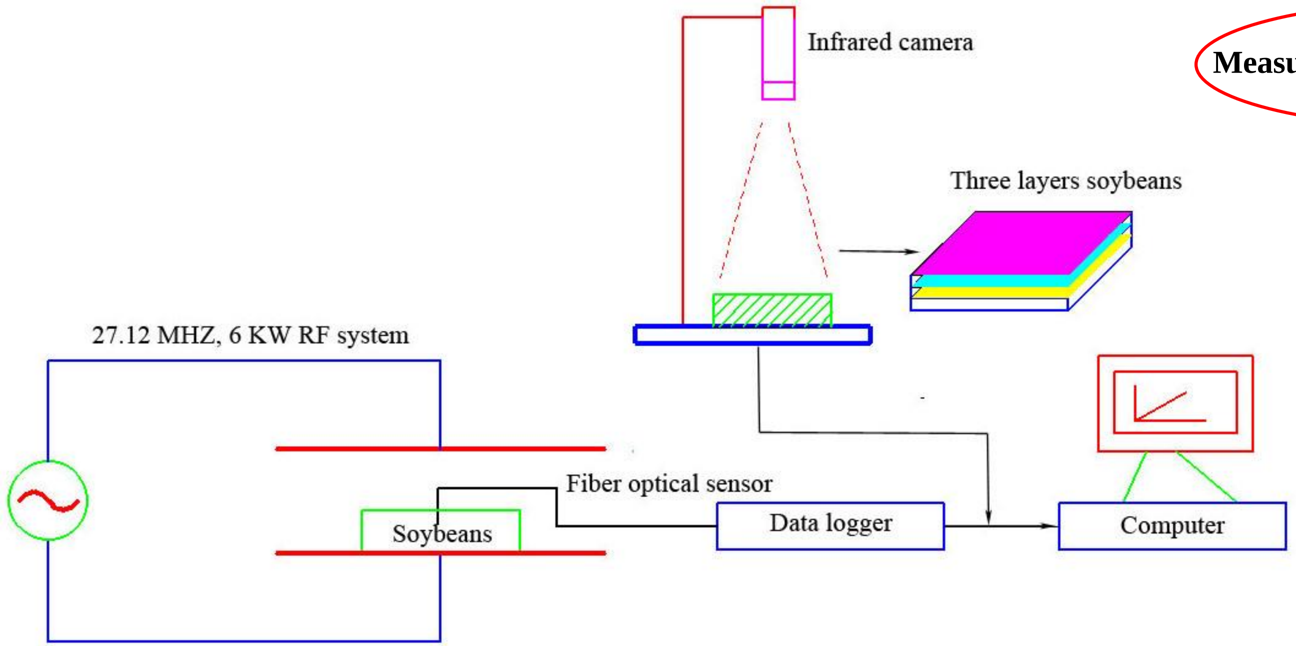
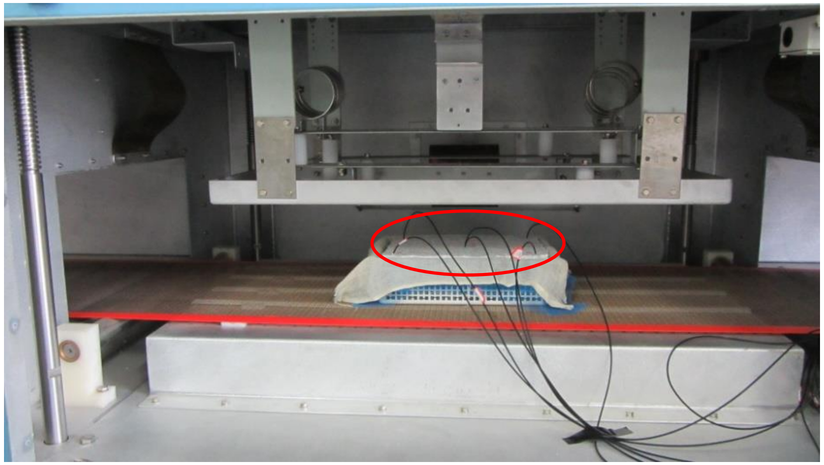


Fig. 2. Dimensions and locations of the plastic container and six fiber-optical sensors (with labeled locations) for measuring temperature distributions of cylinder-shaped ($12H \times 2.5D$ mm^2) insects (1, 2, and 3) and dry soybeans (4, 5, and 6) in each layer inside the rectangular container during RF treatments (all dimensions are in cm).

Model validation

Measurement procedure within 25 s





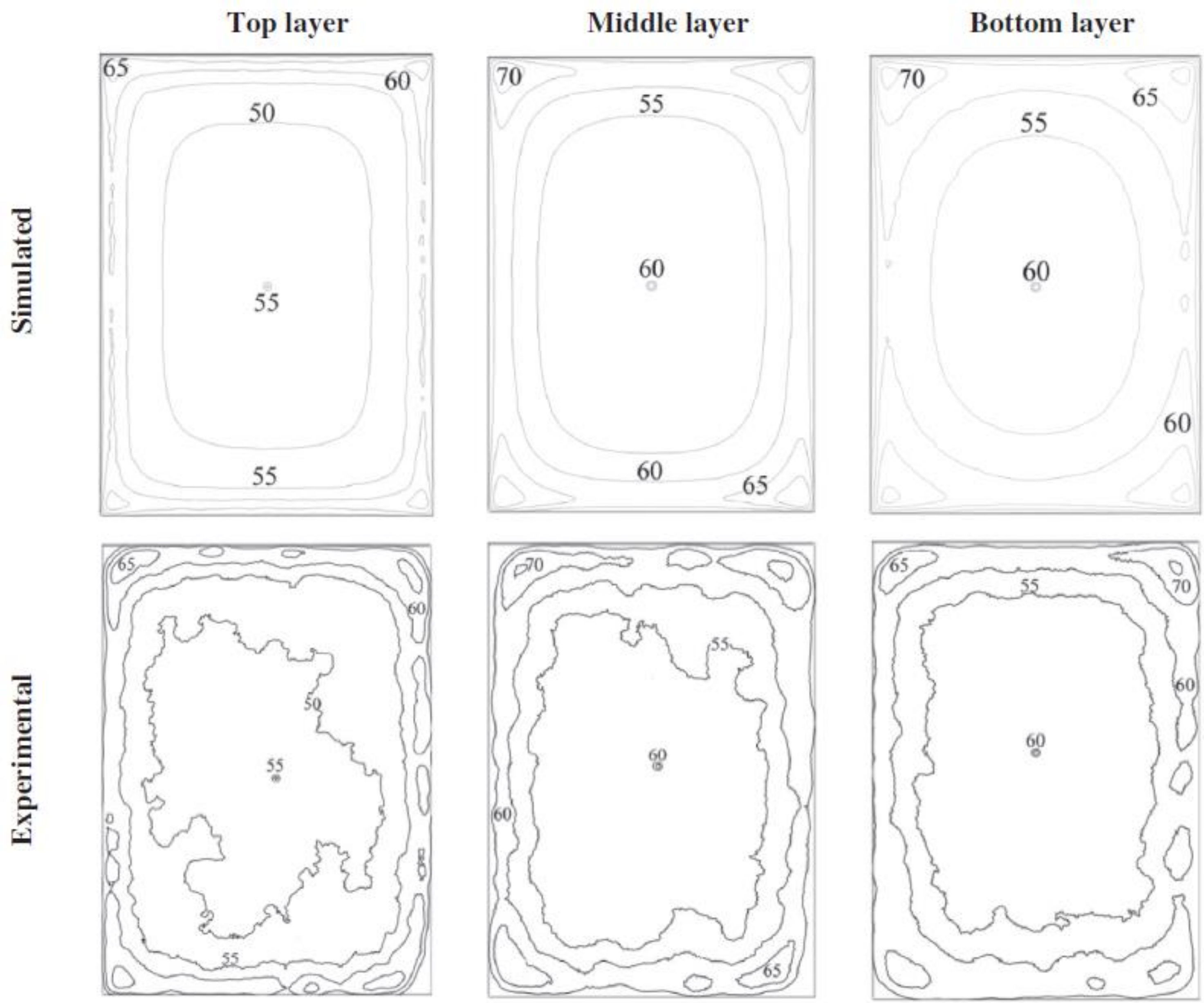


Fig. 7. Comparison of simulated and experimental temperatures for top, middle, and bottom layers of dry soybeans and three insects at the geometric center of each layers (2, 4, and 6 cm from the bottom of sample), placed in a polypropylene container ($30 \times 22 \times 6$ cm^3) on the ground electrode with insect body positioned vertically under the same RF heating conditions.

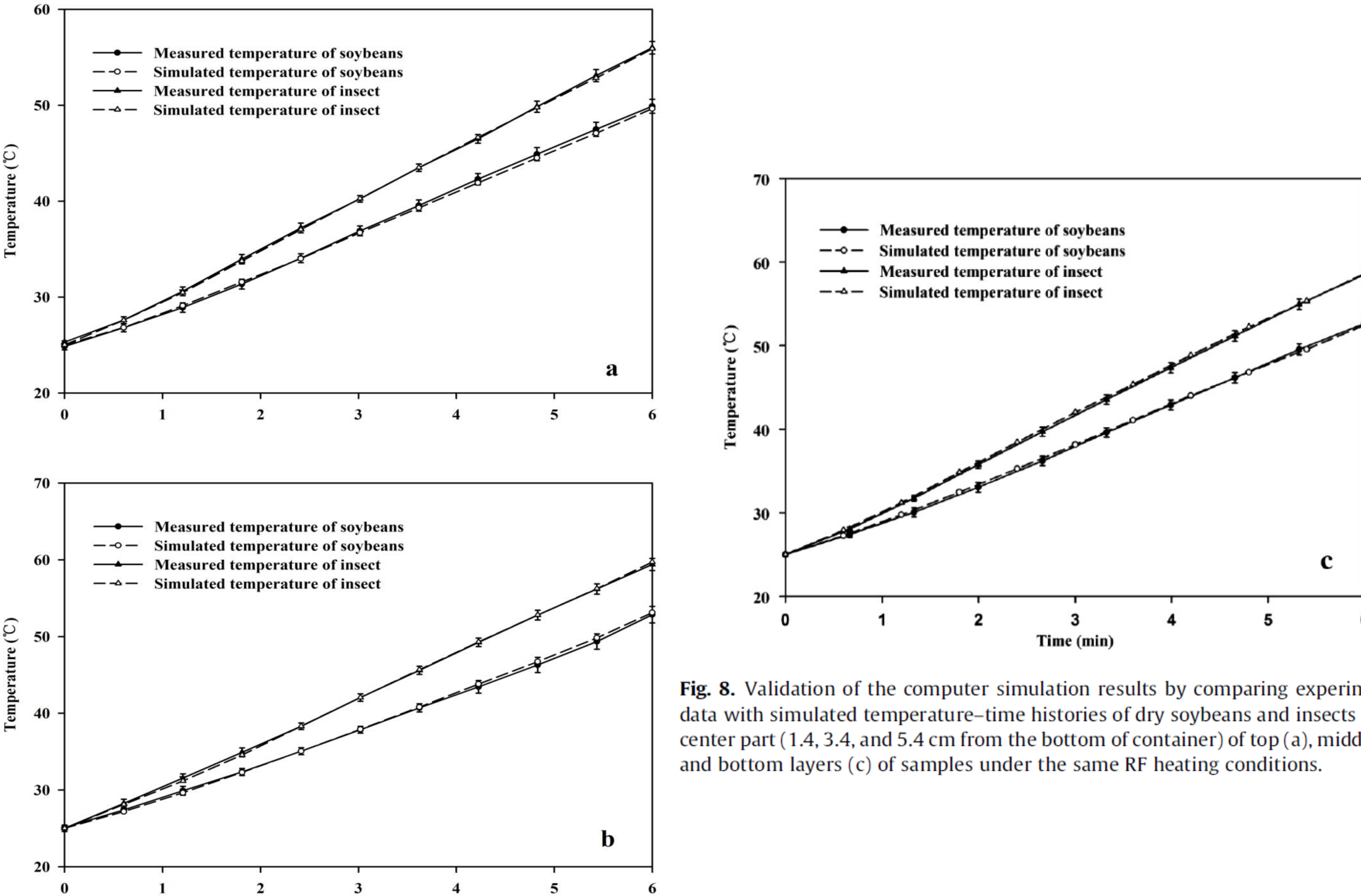


Fig. 8. Validation of the computer simulation results by comparing experimental data with simulated temperature–time histories of dry soybeans and insects at the center part (1.4, 3.4, and 5.4 cm from the bottom of container) of top (a), middle (b), and bottom layers (c) of samples under the same RF heating conditions.

Model application

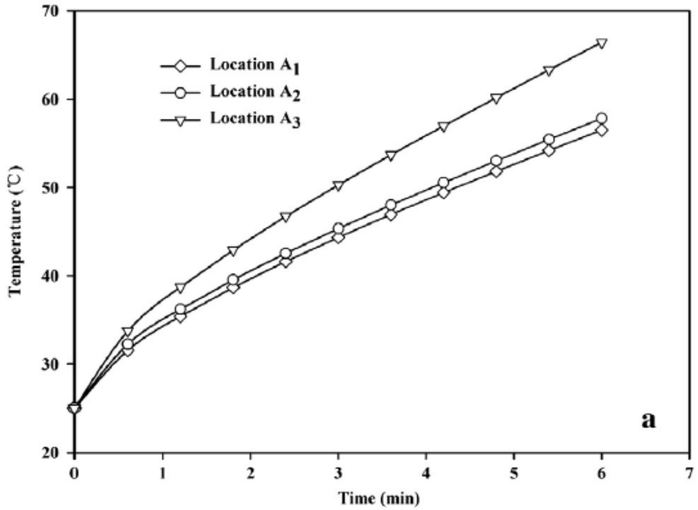


Table 2
Comparison between simulated and experimental average (Ave) and standard deviation (SD) temperatures (°C) of dry soybeans at three horizontal layers after 6 min RF heating at a fixed electrode gap of 12 cm and initial temperature of 25 °C.

Layer	Simulated		Experimental	
	Ave	SD	Ave	SD
Top	53.77	4.90	53.39	4.93
Middle	57.94	5.28	56.14	5.24
Bottom	56.22	5.96	55.43	5.83

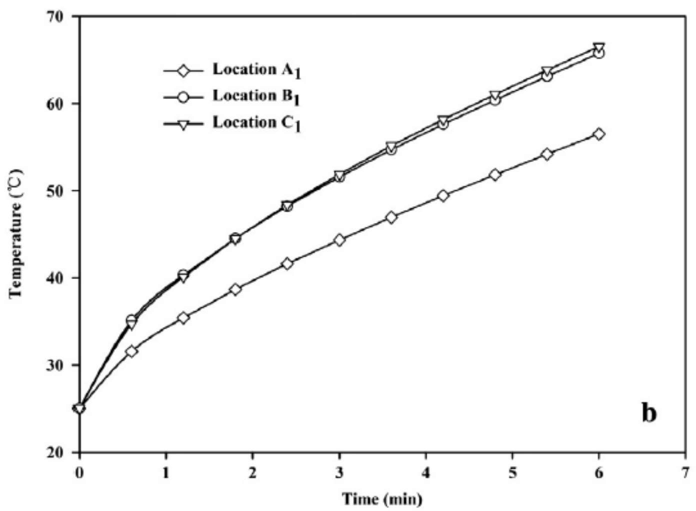


Fig. 9. Computer simulated temperature profiles at the geometric center of insects located at each positions in the top surface layer (A_1, A_2, and A_3) (a) and center part of three horizontal layers (A_1, B_1, and C_1) (b) with insect body positioned vertically under the same RF heating conditions.

Table 3
Simulated average (Ave), maximum (Max) and minimum (Min) temperatures (°C) of insects over the volume at nine different locations within the soybeans.

Layer		Min	Max	Max–Min	Ave
Top layer	A_1	55.32	59.87	4.55	57.71
	A_2	55.14	61.60	6.46	58.04
	A_3	61.23	72.12	10.89	66.00
Middle layer	B_1	63.41	65.67	2.26	64.83
Bottom layer	C_1	64.85	68.33	3.48	66.40

Model application

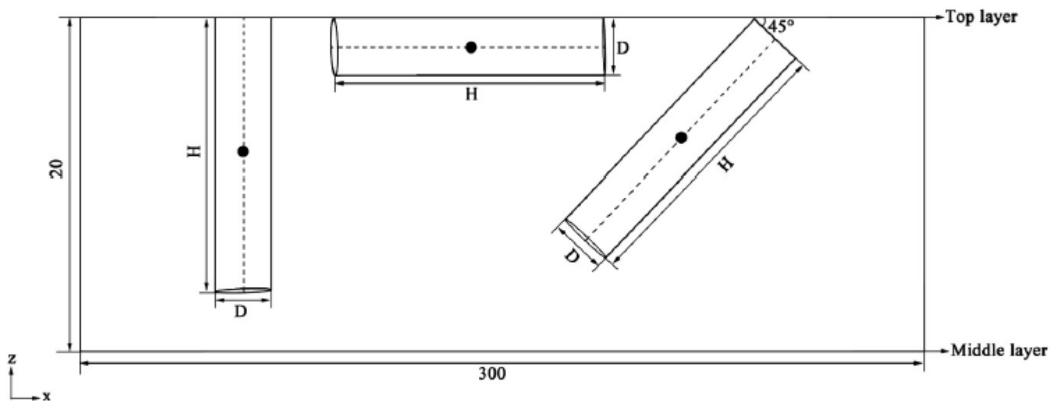


Fig. 4. Different placements (vertical, oblique and horizontal in cross-section of x–z) of insects at the top surface center of dry soybeans with electrode gap of 12 cm, simulated RF heating time of 6 min, and initial temperature of 25 °C (all dimensions are in mm).

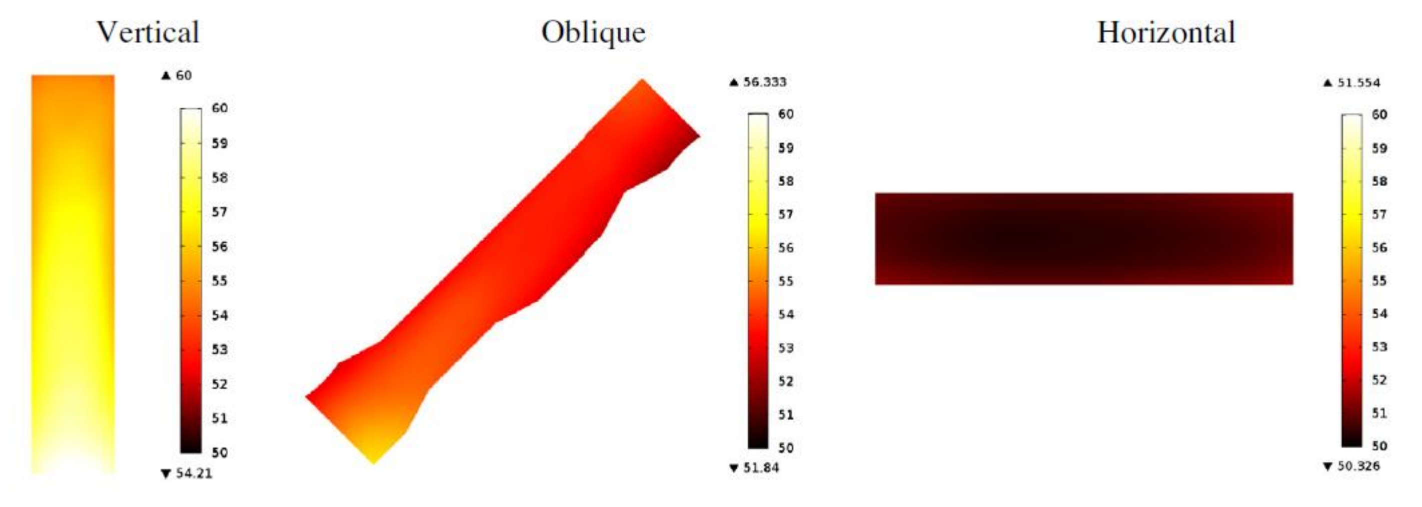


Fig. 10. Computer simulated temperature (°C) distribution of insects ($12H \times 2.5D$ mm^2) along the central cross-sectional with three different placements (vertical, oblique and horizontal) located at the top surface center of soybeans under the same RF heating conditions.

Model application

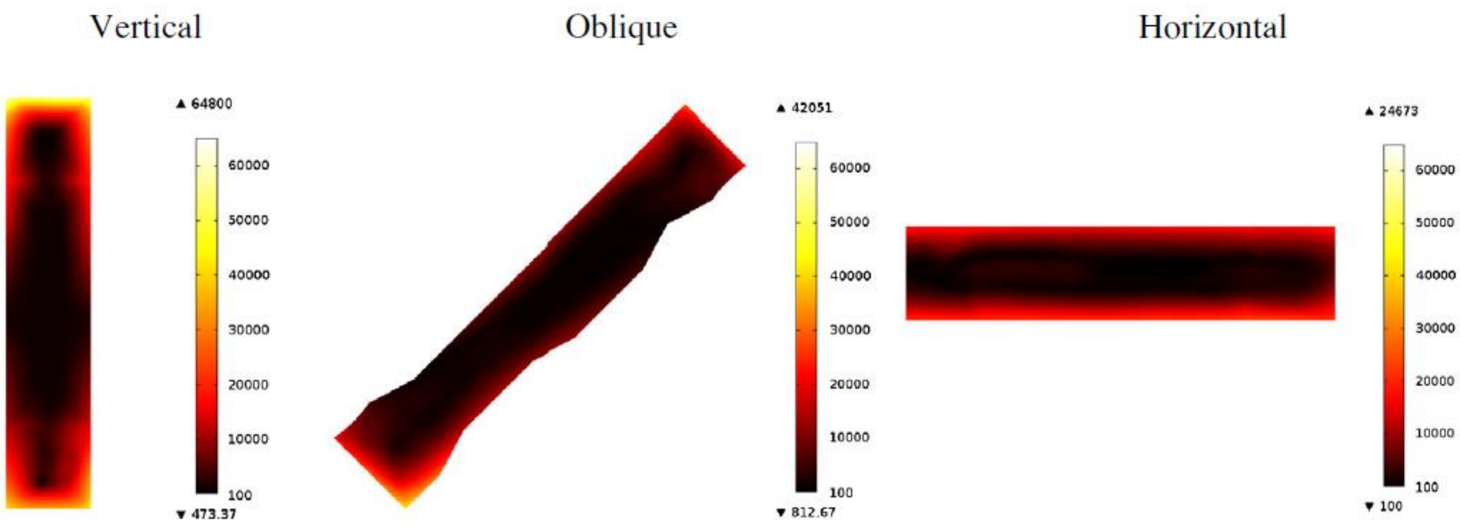


Fig. 11. Simulated electric field (V/m) distribution of insects ($12H \times 2.5D\ mm^2$) along the central cross-sectional with three different placements (vertical, oblique and horizontal) located at the top surface center of soybeans under the same RF heating conditions.

The results demonstrated that the heating rate for **vertically placed insect** was much higher than that obliquely and horizontally placed insects.

Model application

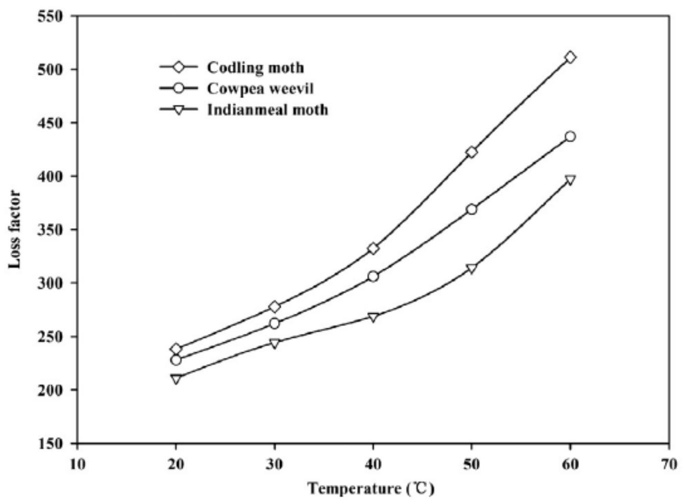


Fig. 5. Dielectric constant and Loss factor for three different insects at temperature range of 20–60 °C and frequency of 27.12 MHz [11,12].

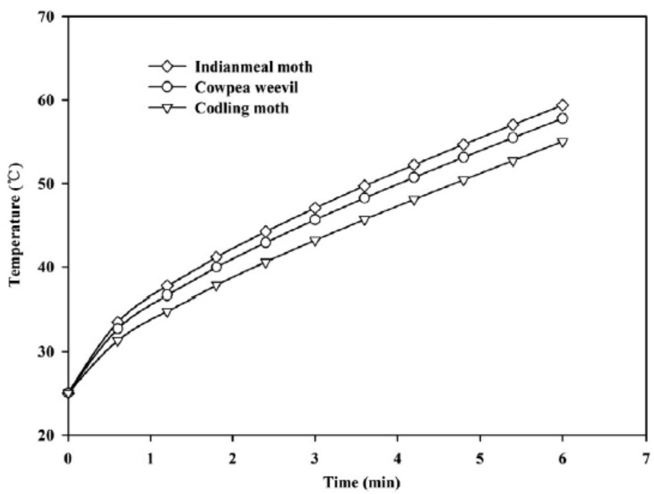


Fig. 13. Computer simulated temperature–time histories at the geometric center of insects located at the top surface center of soybeans with three different dielectric properties and insect body positioned vertically under the same RF heating conditions.

Table 5
Simulated average (Ave), maximum (Max) and minimum (Min) temperatures (°C) of insects over the volume with three different dielectric properties located at the top surface center of soybeans.

Material	Dielectric properties	Min	Max	Max–Min	Ave
Indianmeal moth	$(0.81 * T + 63.12) - j(4.42 * T + 109.86)$	55.32	59.87	4.55	57.71
Cowpea weevil	$(0.48 * T + 46.60) - j(5.25 * T + 110.40)$	54.55	59.26	4.71	56.58
Coding moth	$(0.35 * T + 61.76) - j(6.91 * T + 79.98)$	52.97	58.12	5.15	53.00

T-temperature ($20 \leqslant T \leqslant 60$ °C).

The **loss factor** is the dominant factor influencing differential energy absorption from the RF field.

Model application

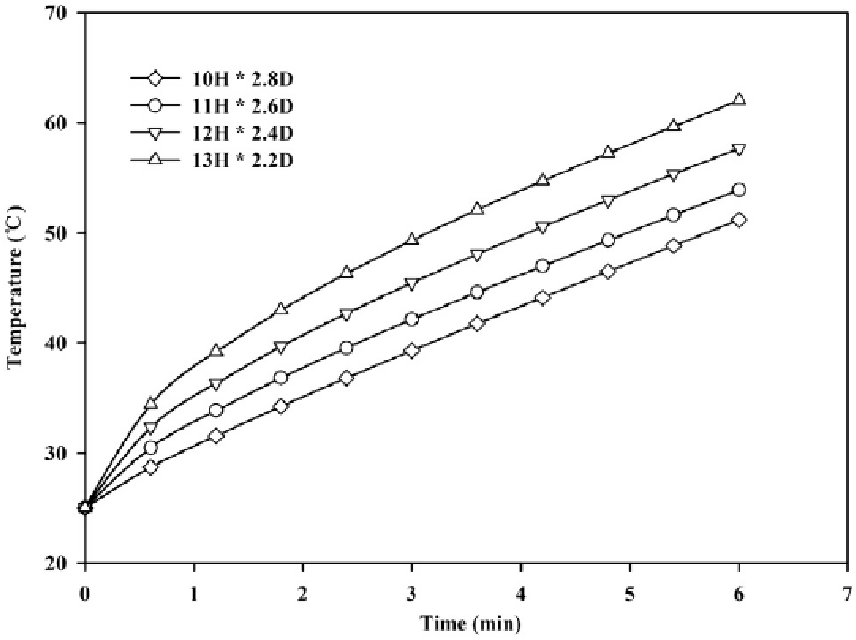


Fig. 14. Computer simulated temperature–time histories at the geometric center of insects located in the top surface center of dry soybeans with four different sizes and insect body positioned vertically under the same RF heating conditions.

Table 6
Simulated average (Ave), maximum (Max) and minimum (Min) temperatures (°C) of insects over the volume with four different sizes located at the top surface center of soybeans.

Size (mm^2)	Min	Max	Max–Min	Ave
$10H \times 2.8D$	51.38	55.20	3.82	52.77
$11H \times 2.6D$	53.47	57.56	4.09	54.77
$12H \times 2.4D$	56.57	60.28	3.71	58.18
$13H \times 2.2D$	62.23	64.00	1.77	62.23

The temperature increased slowly for **the short and fat insect**, but small insects were much easy to be killed during RF heating due to relatively fast heating.

Conclusions

- Simulated and experimental results both showed that **cold spots** were located at the center part of each layer.
- The mean **temperature differences** between insects and soybeans at the top, middle, and bottom layers were 5.9, 6.6, and 6.2 ℃, respectively.
- Simulated results showed that when the insect was placed on the **top surface center**, **horizontally placed** in the host medium, and **large insect size** would cause relatively slow heating rate as well as low average temperature.
- The developed simulation model can help designing the practical treatment protocol to maintain selective RF heating and achieve the optimum product temperatures for **completely controlling** the insect without adverse effects on host product quality.

Acknowledgements

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Thank you!