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A strategy to simulate radio frequency heating under mixing conditions

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Overview

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1. Introduction

- Because of rapid and volumetric heating, RF treatment has been studied for **disinfestations** in postharvest agricultural products.
- The major obstacle for implementing RF technology is the **non-uniform heating**.
- **Mixing** has been used to improve the RF heating uniformity and usually used in commercial systems, it is important to determine **the effects of mixing** on temperature distributions in RF treated products.

Objectives

- **Develop a computer simulation model** for wheat samples at a 6 kW, 27.12 MHz RF system using COMSOL.
- **Validate** the simulation model by comparing with the experimental temperature profiles of wheat at three layers without mixing.
- **Apply** the validated model to **evaluate the effects** of **mixing** on RF heating patterns using **uniformity index**

2. Materials and methods

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

Material properties	Wheat	Aluminum [a]	Air [a]	Polypropylene [a]
Heat capacity C_p (J kg^{-1} K^{-1})	2670 [d]	900	1200	1800
Density ρ (kg m^{-3})	860	2700	1.2	900
Thermal conductivity k (W m^{-1} K^{-1})	0.15 [c]	160	0.025	0.2
Dielectric constant (ε')	4.3 [d]	1	1	2.0 [b]
Loss factor (ε'')	0.11 [d]	0	0	0.0023 [b]

3. Model development

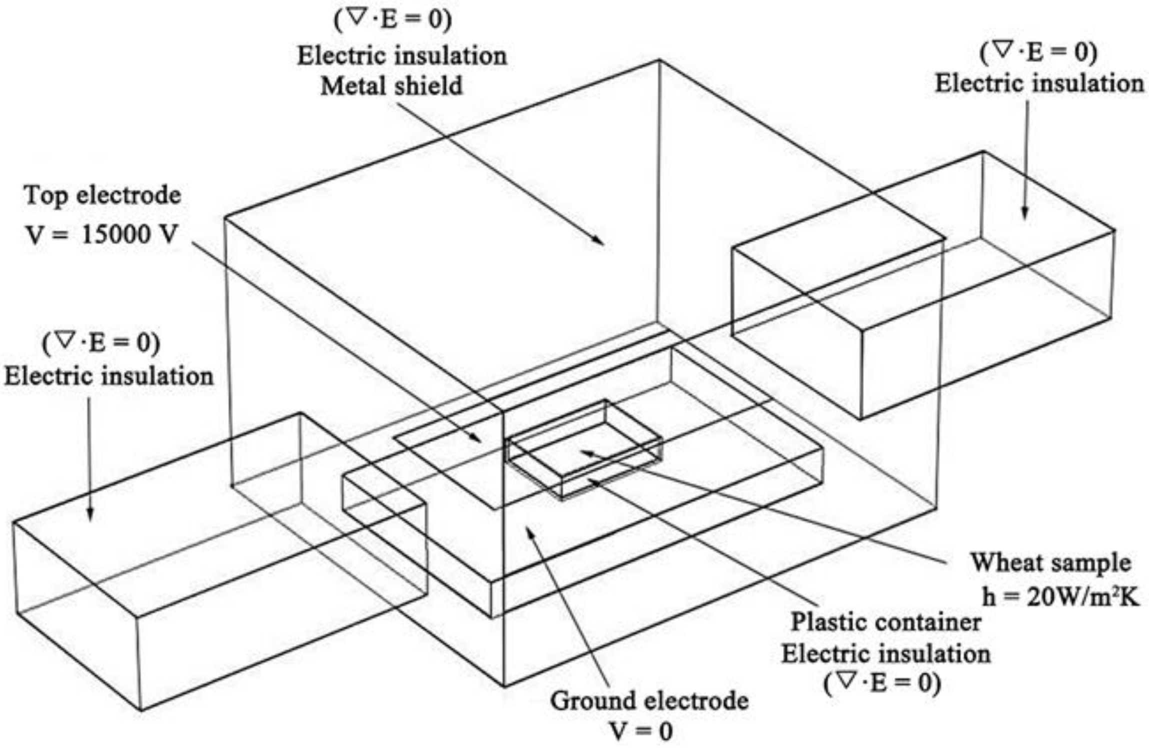


Fig. 1. 6 kW, 27.12 MHz free-running oscillator RF heating system and boundary conditions of RF system used in simulation.

Governing equations

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

RF power conversion: $$Q=2\pi f\varepsilon_0\varepsilon''\left|\vec{E}_{\mathrm{m}}\right|^2$$

Heat transfer： $$\rho C_P\frac{\partial T}{\partial t}=\nabla(k\nabla T)+Q$$

Electric field intensity: $$\left|\vec{E}_m\right|=\frac{V}{\sqrt{\left(\varepsilon' d_0+d_m\right)^2+\left(\varepsilon'' d_0\right)^2}}$$

- **COMSOL Multiphysics V4.3a (Joule heating model (electric current module & heat transfer in solid module))**

3. Model development

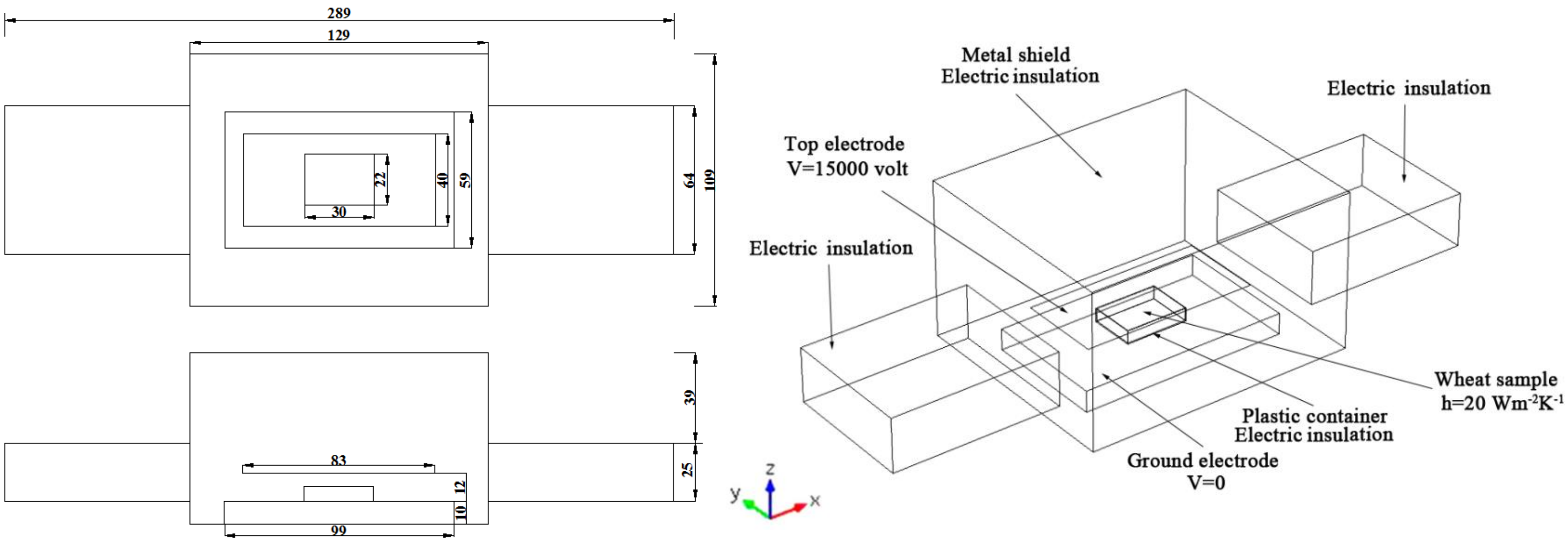


Fig. 2. 3-D Scheme (a) and dimensions (b) of the 6 kW 27.12 MHz RF system and food load (wheat sample) used in simulations (all dimensions are in cm).

3. Model development

Model assumptions:

1. After each mixing, the temperature distributions of wheat sample were assumed to be uniform, because of small standard deviations after short RF heating at each mixing step.
2. The mass and momentum transfers of moisture were neglected due to a short time (3.5 min) RF heating.

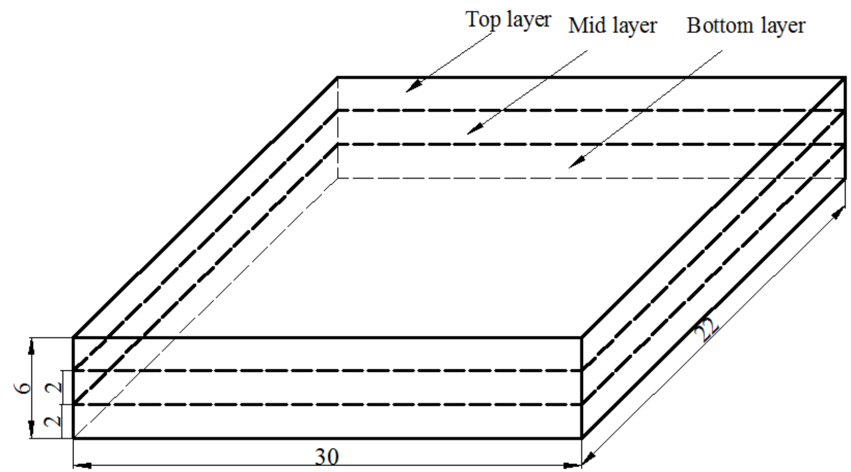
3. Model development

In the simulation model, after one-time mixing for one interval RF heating, the average temperature of wheat samples was regarded as the initial temperature for the next interval RF heating until all mixing times were completed. The temperature drop (ΔT, °C) due to heat loss during each mixing process was considered in simulation model as follows:

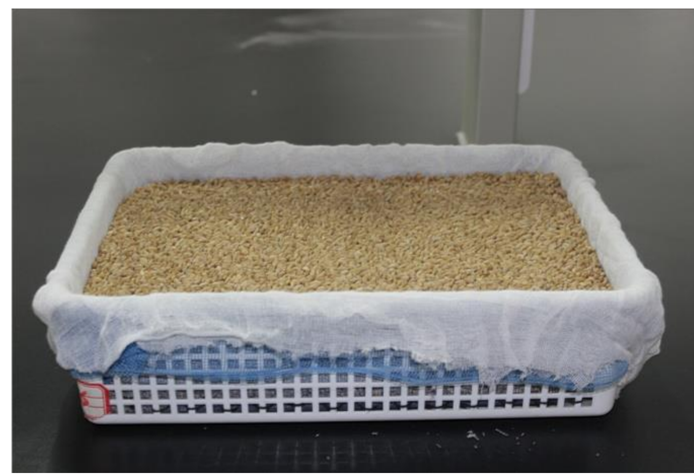
$$\Delta T = \frac{hA(T_f - T_a)\Delta t}{\rho C_p V}$$

where h, the convective heat coefficient which was estimated to be 28 W m^{-2} K^{-1} with forced convection during the whole mixing process (Wang et al., 2007a), A and V are the whole surface areas (0.1944 m^2) and volume (0.00396 m^3) of the wheat sample, respectively. T_f and T_a are the final average temperature of wheat sample after RF heating prior to each mixing and the ambient air temperature (25 °C), respectively. Δt is the total time (60 s) taken during each mixing process.

4. Model validation



- **Rectangular plastic container**
  - Inner dimension (30 × 22 × 6 cm^3)
- **3.39 kg of wheat sample**
  - Sample height: 6 cm
  - Each layer's height: 2 cm
  - Initial temperature: 25 ° C
  - Electrode gap: 12 cm
  - **Gauze**
  - Thickness of 0.28 mm, mesh opening of 1 mm
  - Facilitate surface temperature mapping in three layers.



4. Model validation

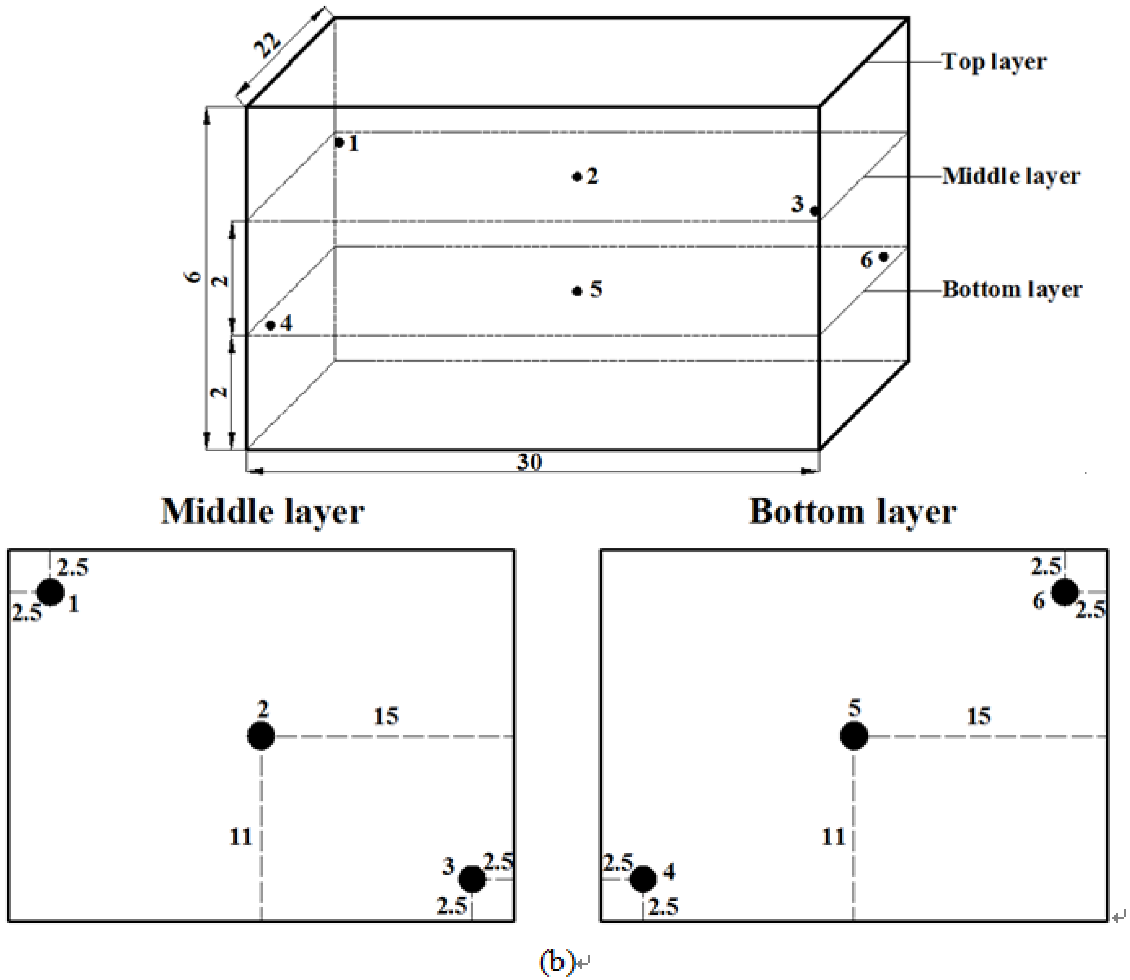


Fig. 3. Top layer (a) and the locations of six points (b) in wheat samples used for surface and interior temperature measurements in mixing experiments (all dimensions are in cm).

4. Model validation

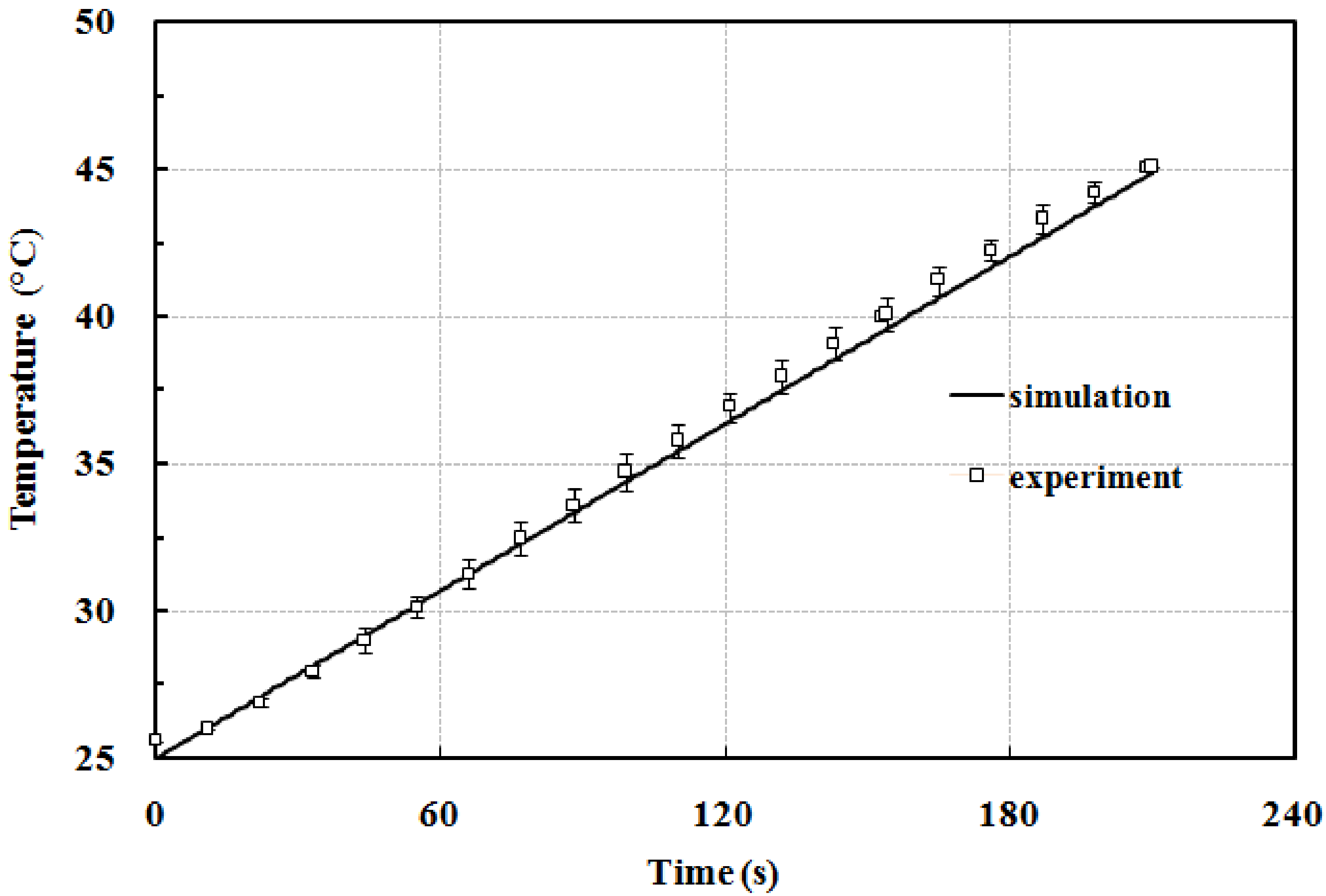


Fig. 4. Experimental and simulated temperature–time histories of wheat sample at the geometry centre of the sample during 3.5 min stationary RF heating.

4. Model validation

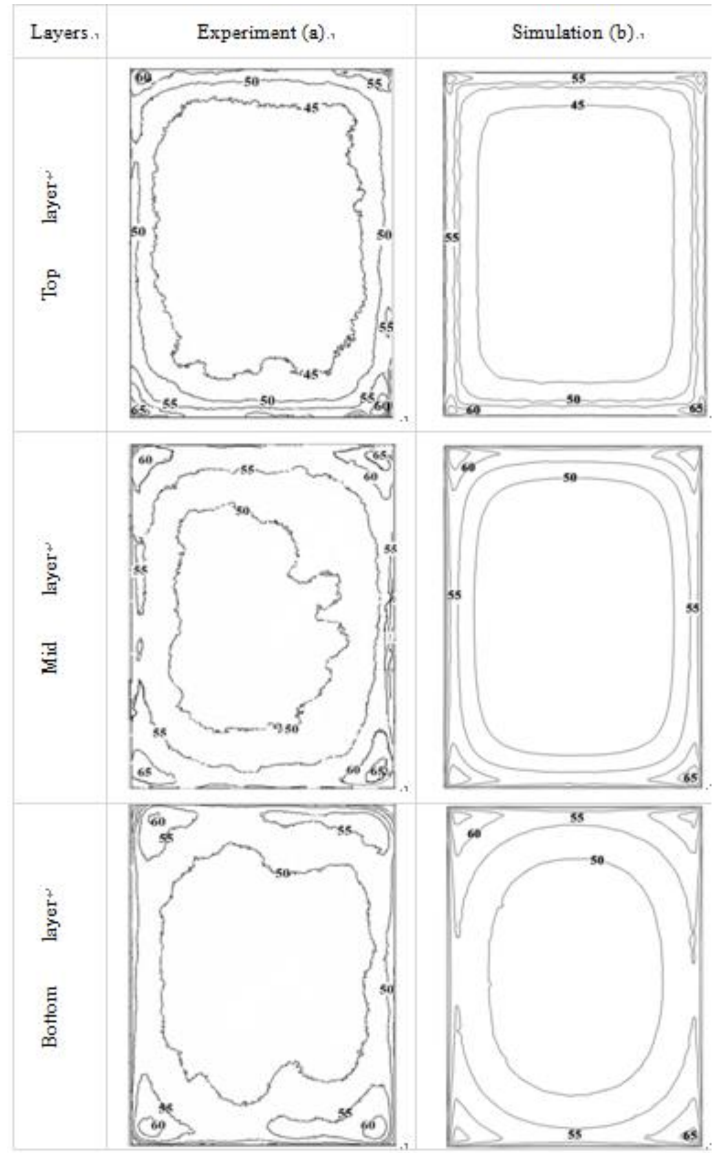


Fig. 5. Experimental and simulated temperature distributions (° C) of wheat samples at top, middle, and bottom layers (20, 40, and 60 mm from the bottom of sample) in a plastic container (300×220×60 mm^3) on the center of the ground electrode, after 3.5 min RF heating without mixing at an initial temperature of 25 ° C and a fixed electrode gap of 120 mm.

4. Model validation

Table 2. Comparison between experimental and simulated average and standard deviation temperatures (°C) of wheat samples at three horizontal layers after 3.5 min RF heating without mixing at a fixed gap of 120 mm and initial temperature of 25 °C.

Layer	Experiment	Simulation
Top	48.7±4.1	48.9±5.5
Middle	51.2±3.2	52.4±5.5
Bottom	52.0±2.2	52.4±5.1

4. Model validation

Table 3. Comparison of temperature distribution (Average±SD) of wheat samples between experiment and simulation subjected to 3.5 min RF heating before and after mixing at a fixed gap of 120 mm.

Temperatures (°C)		Mixing		
		1st	2nd	3rd
Experiment (surface)	Before mixing	31.3±1.0	37.1±0.8	42.4±0.8
	After mixing	31.1±0.5	36.7±0.6	41.8±0.6
Experiment (internal)	Before mixing	32.3±1.9	38.4±1.8	43.8±1.5
	After mixing	31.5±0.7	37.4±0.3	42.8±0.4
Simulation	Before mixing	31.4±1.4	37.4±1.4	43.3±1.4
	After mixing	31.2±0.0	37.0±0.0	42.6±0.0

4. Model validation

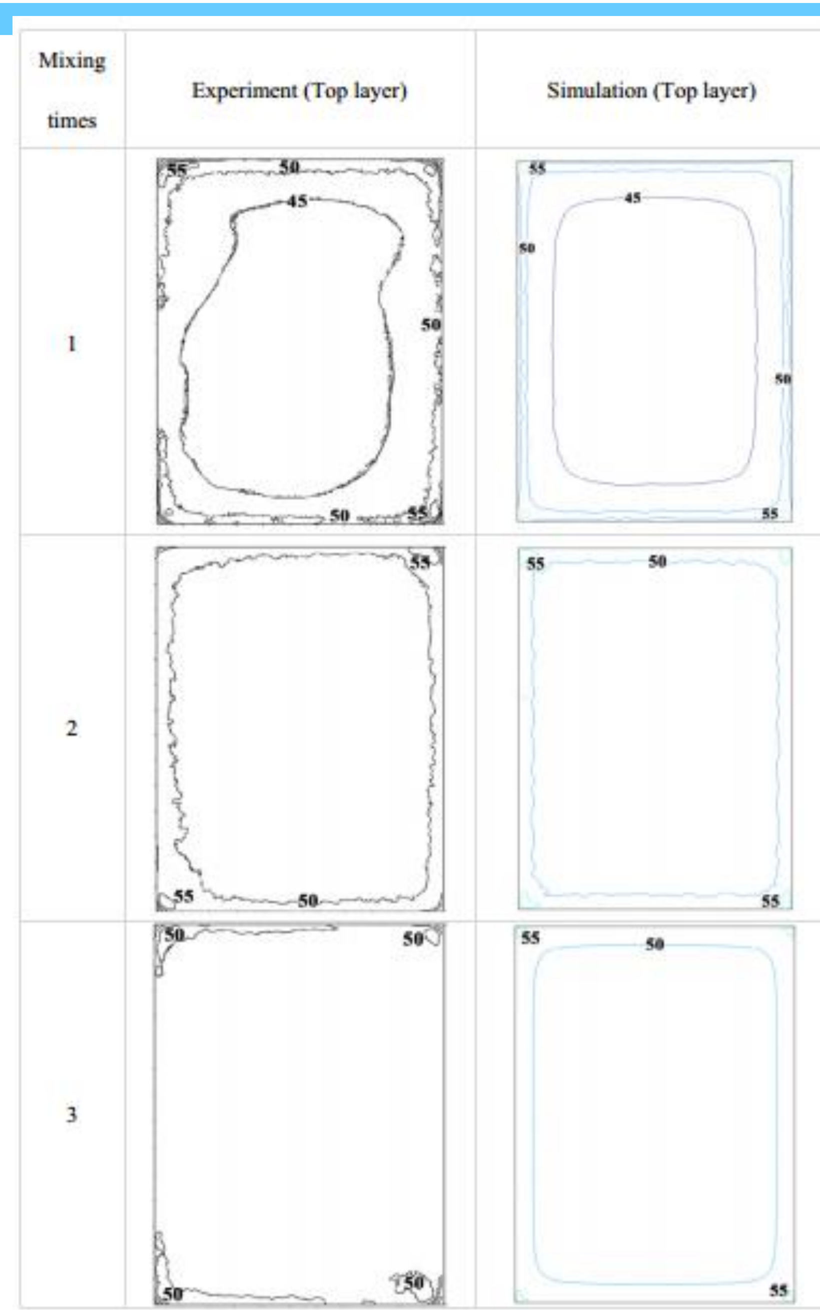


Fig. 6. Experimental and simulated surface temperature distributions (° C) of wheat samples at the top layers corresponded to one, two and three-time mixings during 3.5 min RF heating

4. Model validation

Table 4 Comparison between experimental and simulated surface temperatures of wheat samples at the top layer after 0, 1, 2 and 3 times mixing during 3.5 min RF heating with an initial temperature of 25 °C and a fixed electrode gap of 120 mm.

Mixing times	Experiment (top layers)	Simulation (top layers)
0	48.7 ± 4.1	48.9 ± 5.5
1	47.5 ± 1.6	48.6 ± 3.2
2	47.3 ± 1.1	48.3 ± 2.3
3	47.0 ± 0.9	47.9 ± 1.8

4. Model validation

Table 5
Experimental and simulated wheat temperatures at interior six locations as influenced by mixing times during 3.5 min RF heating with an initial temperature of 25 °C and a fixed electrode gap of 120 mm.

Mixing times	Locations	Experimental temp (°C)	Simulated temp (°C)
0	1	55.5 ± 0.08	59.5
	2	46.0 ± 0.21	46.5
	3	56.7 ± 0.14	59.6
	4	55.0 ± 0.28	60.9
	5	47.0 ± 0.22	47.0
	6	53.9 ± 0.15	60.9
1	1	53.1 ± 0.07	54.5
	2	46.6 ± 0.06	47.2
	3	53.7 ± 0.07	54.6
	4	53.6 ± 0.11	55.3
	5	47.7 ± 0.22	47.7
	6	52.4 ± 0.57	55.4
2	1	52.4 ± 0.35	52.6
	2	47.4 ± 0.42	48.1
	3	53.0 ± 0.30	52.8
	4	51.5 ± 0.71	53.2
	5	48.3 ± 0.35	48.4
	6	51.6 ± 0.50	53.3
3	1	50.0 ± 0.57	51.6
	2	49.3 ± 0.06	49.1
	3	51.1 ± 0.43	51.6
	4	50.0 ± 0.57	52.2
	5	48.9 ± 0.11	49.2
	6	49.9 ± 0.15	52.1

5. Model application

The uniformity index value has been used to evaluate the temperature distribution of samples subjected to RF heating which is defined as the ratio of standard deviation to average temperature rise during heating, using the following equation (Wang et al., 2005) :

$$\lambda = \frac{\Delta\sigma}{\Delta\mu}$$

In RF treatments, the smaller index represents better heating uniformity.

5. Model application

Table 6
Comparison of surface and interior temperature distribution (average ± SD) and heating uniformity index (UI) of surface and interior wheat samples subjected to 3.5 min RF heating without and with mixing conditions at a fixed gap of 120 mm.

Temperature distribution and UI	Mixing times			
	0	1	2	3
Experiment				
Surface temperature (°C)	48.7 ± 4.1	47.5 ± 1.6	47.3 ± 1.1	47.0 ± 0.9
Interior temperature (°C)	52.3 ± 4.5	51.1 ± 3.0	50.7 ± 2.2	49.8 ± 0.7
Surface heating UI	0.1738	0.0691	0.0503	0.0403
Interior heating UI	0.1626	0.1157	0.0850	0.0279
Simulation				
Surface temperature (°C)	48.9 ± 5.5	48.6 ± 3.2	48.3 ± 2.3	47.9 ± 1.8
Interior temperature (°C)	55.7 ± 7.00	52.5 ± 3.9	51.4 ± 2.5	51.0 ± 1.4
Surface heating UI	0.2302	0.1335	0.0978	0.0787
Interior heating UI	0.2275	0.1417	0.0932	0.0551
Volume heating UI	0.1960	0.1075	0.0764	0.0603

5. Model application

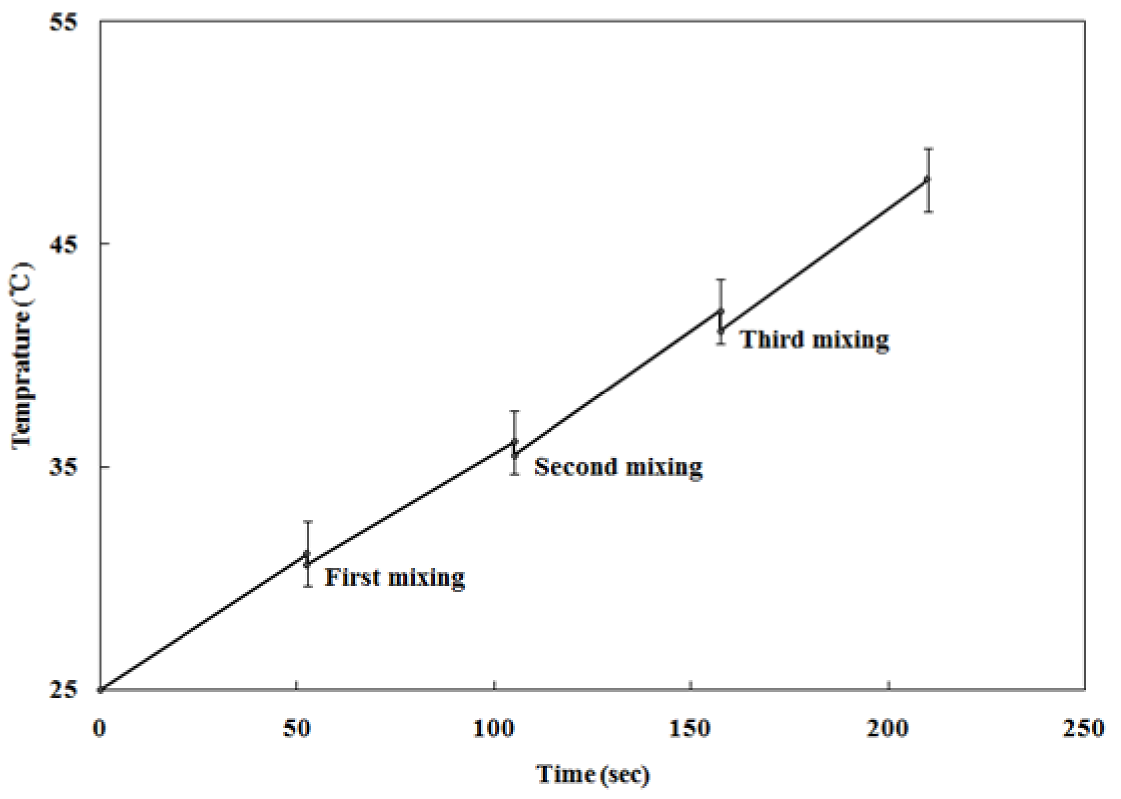


Fig. 7. Change of simulated average and standard deviation temperatures of wheat sample during three-time mixing process for 52.5 s of each RF heating interval.

6. Conclusions

1. The uniformity index (UI) of RF treated wheat samples showed the same decreasing trend with the increasing **mixing times** based on experiment and simulation results.

2. Because of the heat loss during **mixing** process, both the **average temperatures** of surface and interior wheat samples were **reduced** in experiment and simulation.

3. The model can serve as a valuable tool to design and optimize a treatment protocol for industrial-scale RF treatments.

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Thank you!