Development and Validation of Analytical Charts for Microwave Heating of Selected Packaged Food Products

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Introduction

Microwave heating has wide applications in the food industry, such as thawing, drying, pasteurization and sterilization. Microwave heating has gained popularity due to its higher heating rate and minimal nutritional degradation [1].

Figure 1 Some of the microwave heating applications: (a) thawing and (b) pasteurization of ready-to-eat meals

In microwave heating, understanding the relationship among the food dielectric properties, temperature, salt content, and thickness is critical in predicting the central layer heating rate accurately. Accurate prediction of the heating rate will ensure food safety [2].

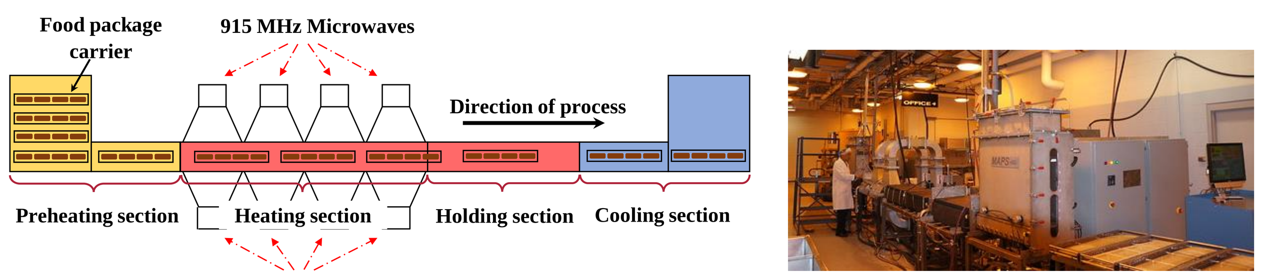

Figure 2 Microwave-assisted pasteurization system (MAPS) developed at WSU

Objectives:

i. To develop an analytical chart that clarifies the relationship among the dielectric properties, temperature, salt content and thickness to accurately predicted the heating rate.
ii. Illustrate the application of the chart for prediction of the heating rate and selection of preheating temperature as well as salt content for the maximum heating rate.
iii. Validate the chart by experimental heating rates and heating pattern tests.

Materials and Methods

The main conditions and assumptions in this research were:

I. A 915 MHz single-mode electromagnetic plane wave was applied that traveled through the water to the food.
II. The food samples were homogeneous and rectangular-shaped.
III. The microwave power was considered as the only heat source.

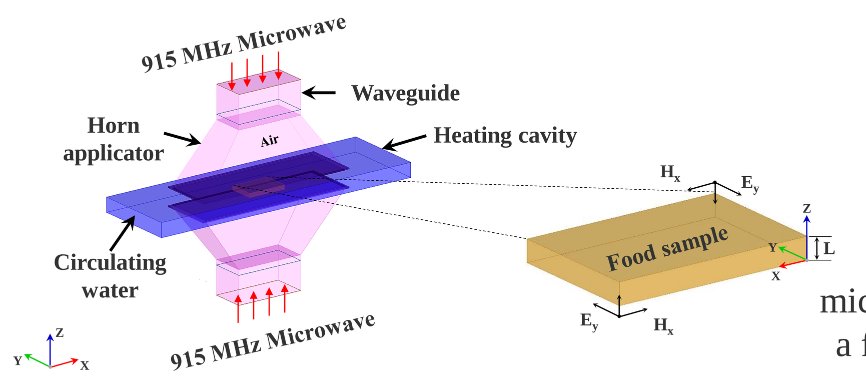

Figure 3 A single-mode microwave heating cavity with a food sample, L = thickness

Based on the conditions and assumptions, the electric field (V/m), power dissipation (W/m^3) and heating rate (°C/sec) at the center of the food are given by equations (1), (2) and (3), respectively [2].

$$E = \frac{T_{w/f} E_O}{1 + R_{w/f} e^{-\gamma_f L}} \left(e^{-\gamma_f Z} + e^{-\gamma_f (L-Z)}\right) \qquad (1)$$

$$P(z) = 2\pi f \varepsilon_o \varepsilon'' |E|^2 \qquad (2) \qquad \frac{dT}{dt} = \frac{P(z)}{\rho C_P} \qquad (3)$$

where the subscript *w* and *f*, denote water and food, respectively. In equation (1), E_O, T, R, and γ represent the incident electric field intensity, the transmission coefficient, the reflection coefficient, and the propagation constant, respectively. In equation (2), f, ε_o and ε'' represent the frequency, the dielectric permittivity of vacuum, and the dielectric loss factor, respectively. In equation (3), dT is the temperature difference, dt is the time difference and ρC_P is the volumetric specific heat.

Mashed potato, pea and rice samples were prepared, and their dielectric properties and volumetric specific heat were measured using an HP 8752C Network Analyzer with 85070B open-end coaxial probe and a Q1000 Differential scanning calorimeter, respectively as described by [2].

Chart Development:

1. The dielectric loss factors were measured and plotted against temperature at various salt contents (Figure 4).
2. Applying Equations (1), (2) & (3), as shown in Figure 5, the heating rate was determined and plotted against the loss factor (Figure 6).

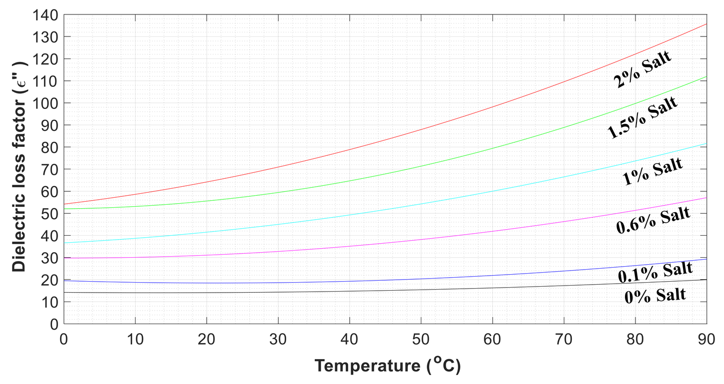

Figure 4 Relationship between temperature and the loss factor in mashed potato samples

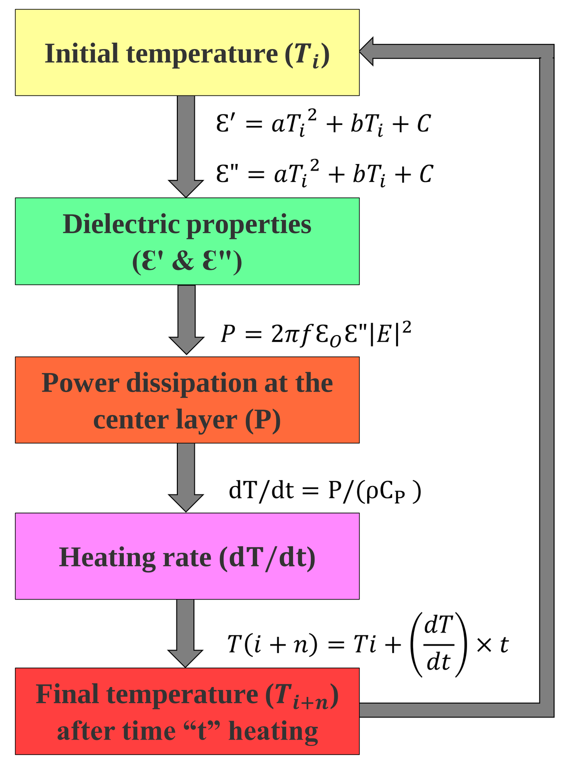

Figure 5 Loop iteration for the heating rate prediction

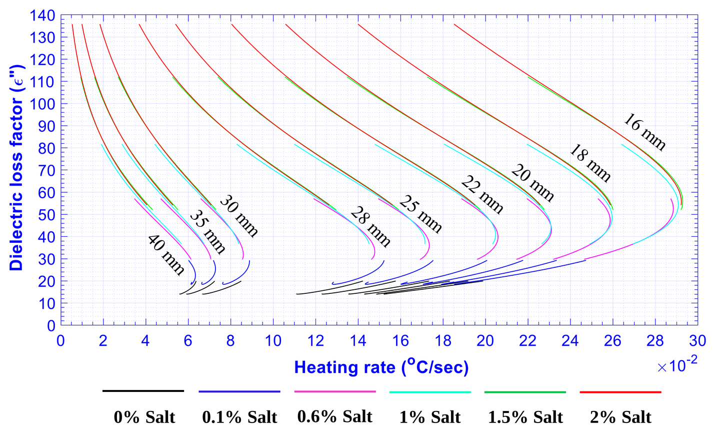

Figure 6 Relationship among the dielectric properties, thickness and heating rate in mashed potato samples

3. Finally, Figures 4 and 6 were superimposed using MATLAB software, as shown in Figure 7. The newly developed chart elucidates the relationship among the dielectric properties, temperature, salt content, thickness and heating rate.

Results and Applications

- In reading the charts (Figure 7 – 9), the heating rate curves, and the temperature lines must go together according to their colors.
- The black dashed lines represent the dielectric constant values, which increase with step 5 in the direction of the arrow.

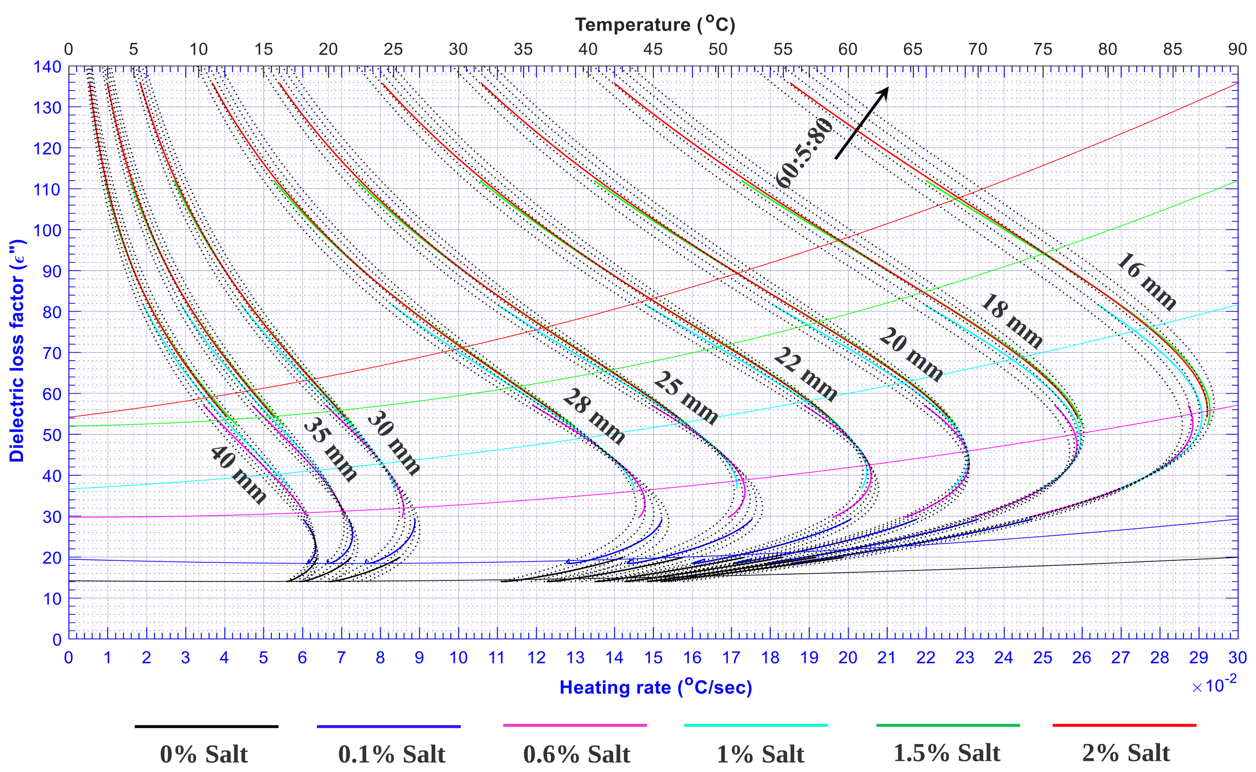

Figure 7 Analytical chart of mashed potato samples in the MAPS

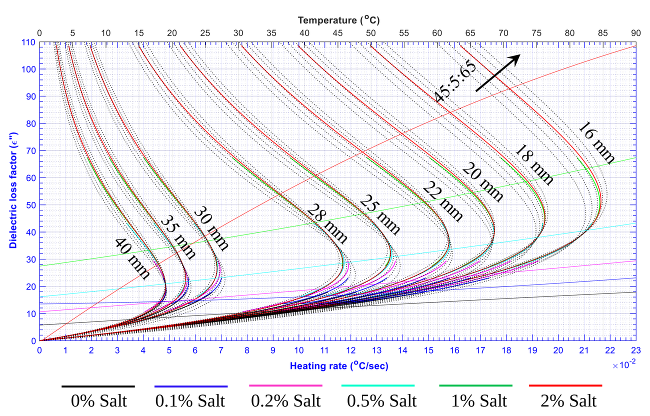

Figure 8 Analytical chart of pea samples in the MAPS

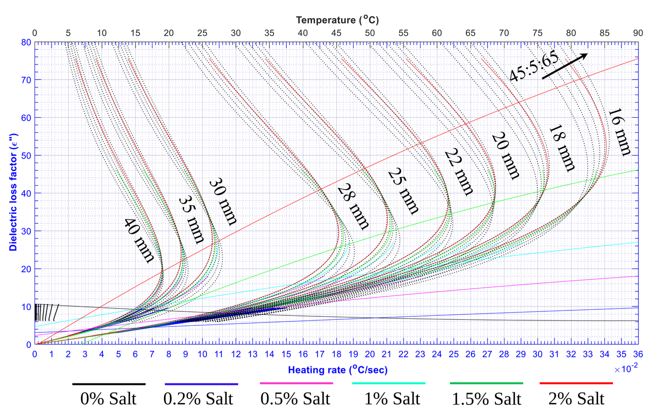

Figure 9 Analytical chart of rice samples in the MAPS

Applications of the charts:

The charts provide the following aspects of information.

I. Dielectric constant: start from temperature → move vertically until the intersection with the salt content line → move horizontally to read the value regardless of thickness.

II. Preheating temperature: start a bit lower from the heating rate curve vertex → move horizontally until the intersection with the salt content line → move vertically to read the temperature.

III. Heating rate: start from temperature → move vertically until the intersection with the salt content line → move horizontally to read the value of the heating rate.

IV. Heating time: start from temperature (initial and target) → move vertically until the intersection with the salt content line → move horizontally to read the values of the heating rates, divide dT by the average heating rates.

V. Optimal salt content: start from the initial and target temperatures, determine the range of heating rates for various salt contents. The salt content that gives a maximum average heating rate will be the optimum.

Validation of the Chart

- In the validation, linear regression models showed that the predicted and experimental temperatures were fit with higher R^2 values (Figure 10).
- More than 95% of the standardized residuals were between the -2 and +2 range.
- The predicted heating rates agreed with the experimental results at various thicknesses and salt contents (Figure 11).
- The predicted optimal salt content to heat the three samples from 60 to 120 °C agreed with the experimental heating pattern test (Figure 12).

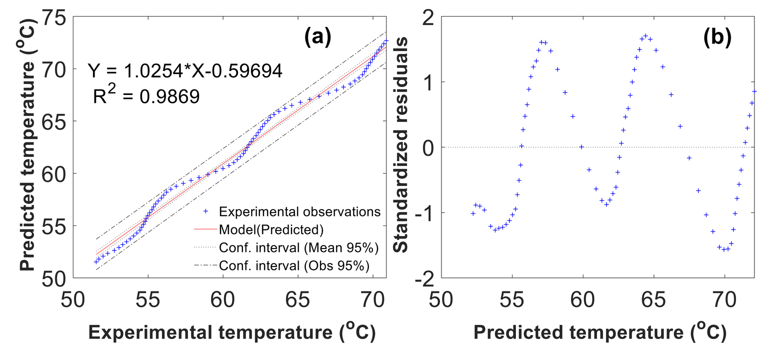

Figure 10 Linear regression fit (a) and residuals (b) of 0% salt and 22 mm thick

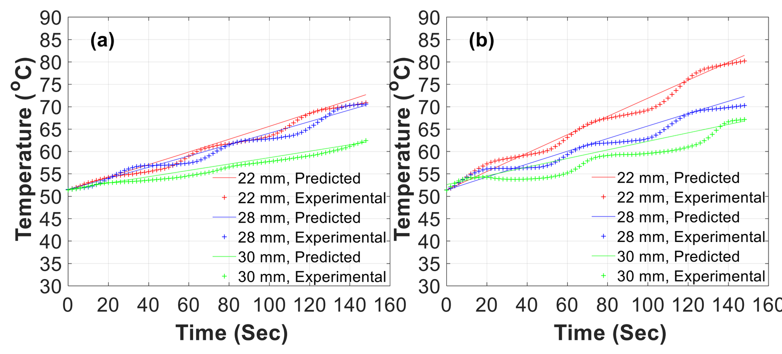

Figure 11 Heating rates of different thickness samples: 0% (a) and 0.6% salt (b)

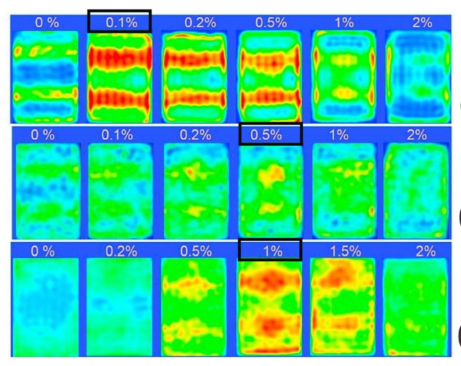

Figure 12 Experimental heating patterns of mashed potato (a), pea (b) and rice (c) samples

Conclusion and Recommendations

- An analytical chart was developed that clarifies the relationship among the dielectric properties, temperature, salt content, thickness and heating rate for three distinct products.
- Linear regression models (R^2 > 0.95) and experimental heating pattern tests showed that the charts are accurate.
- Using the charts can save significant time and resources in the processing of the products and the MAPS process development.
- Similar charts can be developed for various food products.

References

1. J. Tang, "Unlocking Potentials of Microwaves for Food Safety and Quality," J. Food Sci., vol. 80, no. 8, pp. E1776-E1793, Aug. 2015.
2. D. Jain, J. Tang, P. D. Pedrow, Z. Tang, S. Sablani, and Y.-K. Hong, "Effect of changes in salt content and food thickness on electromagnetic heating of rice, mashed potatoes and peas in 915 MHz single mode microwave cavity," Food Res. Int., vol. 119, no. August, pp. 584-595, May 2019.