Modeling and Quality Analysis of Radio Frequency Heating of Low Moisture Foods

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Abstract

Low moisture food is usually considered as high safety food. The low water activity (a_w < 0.85) is a strict environment for pathogenic microbes to grow in the low moisture food. However, the recent outbreaks of *Salmonella* in low moisture foods indicated the possibility of microbiological contamination happened during the harvesting, processing or, transportation of food products. Since the low heat conduction of conventional thermal process in low moisture foods, radiofrequency (RF) treatment has been approved as a promising technology to improve the heating efficiency with its volumetric heating. Nevertheless, non-uniformity heating is still a challenge in RF technology. In addition, there is a knowledge gap in the effect of RF heating on the quality of processed low moisture foods.

To fill in the gaps and address these problems, firstly, we developed and used computer models to understand the improvement of applied immersion fluids on improving the RF heating of the corn flour by fluids immersion and understand its mechanisms. The model showed a good agreement with the experiment results. The modeling results showed that the soybean oil immersion could reduce the electric field distortion to get the best heating uniformity. Also, the higher sample heating rate caused by soybean oil immersion was contributed by both the higher electromagnetic power absorption and lower surface heat loss.

To evaluate the effect of RF heating on the quality of low moisture foods, commercially available bleached and unbleached wheat flour were used as model foods. The quality and functional properties (flour swelling power, sodium carbonate SRC and sucrose SRC) of the flours were evaluated after treatment with using RF heating only and RF & extended air

heating at 80, 85, and 90 °C. The results showed that, generally, the RF heating only did not influence the quality (flour swelling power, sodium carbonate SRC and sucrose SRC) of the flours significantly, while the RF and extended hot air heating had a significant influence on the flour quality, statistically but may not practically.

Keywords: low moisture foods; radio frequency; computer simulation; heating uniformity; quality analysis; heat treatment

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Chapter 1

Introduction

Low moisture food products (such as flours) are commonly considered safe since their low water activity (is normally lower than 0.85), which is undesirable for microbial growth (CAC, 2015; Ozturk et al., 2017). However, the microbiological contaminations can happen during the crop growth, harvesting, processing, transportation, and storage; and the spreading sources include air, dust, water, animal and contaminated equipment (Los et al., 2018; Ozturk et al., 2017a). Furthermore, the pathogenic microbes can stay in the low moisture food products for a long time and cause foodborne problem (Archer et al., 1998). Recently, there are a couple of *Salmonella* outbreaks related to low moisture foods, such as dried coconut, peanut butter, and all-purpose flour, etc. (CDC, 2018, 2012; U.S. Food & Drug., 2019). A small quantity of *Salmonella* can still survive in the products even though the low moisture environment inhibits the growth of *Salmonella* (Finn et al., 2013). Since the microbial contaminations from the production chain are hard to eliminate, the pasteurization at the last step of production is the one of the best ways to ensure food safety.

Thermal processing is common in food pasteurization to ensure the safety of food products. The conventional thermal processes, such as hot air and steam, usually use convective heating to heat the product at the surface and conduct heat to the center of the food product. However, these traditional heating methods usually take a long time to heat the low moisture food products due to the low thermal conductivity, especially for powdered foods that have high porosity. Besides, the low water activity of flour can increase the heat resistance of pathogenic microbes (Archer et al., 1998). Therefore, it's necessary to develop

novel thermal processing technology that can heat the low moisture foods more efficiently.

As a volumetric heating process, radiofrequency (RF) heating shows promise to heat low moisture food products with an increased heating rate andreduced heating time (Boreddy et al., 2014). Unlike the conduction and convection heat transfer of the conventional heating, the electromagnetic wave is produced by the high voltage electrode and able to penetrate into the foods. Therefore, the heat source can be generated within the food by the molecular frictional interaction, which caused by the migrating ions and oscillating alternating electric field generated in the alternating electric field (Piyasena et al., 2003).

RF technology has been extensively studied to process a variety of low moisture food products for disinfestation of almond (Gao et al., 2010), brown rice (Zhou and Wang, 2016), bulk canola seeds (Yu et al., 2015), rice flours (Li et al., 2015), and many other products (Jiang et al., 2020); drying of macadamia nuts (Wang et al., 2013), chicken powder (Ran et al., 2019), potato flour (Zhu et al., 2021) and so on; and pasteurization of corn grain (Zheng et al., 2016), red pepper powders (Hu et al., 2018), and wheat flours (Liu et al., 2018), etc. Many of these studies proved the advantage and productivity of the RF treatment in the industry application.

Although many researches showed the great promise of RF treatment on uniform heating, it is still a challenge in RF processing. Since many factors (dielectric properties, sample geometry and position, and electrode configuration, etc.) can cause the uneven distribution of electric field, which result in the non-uniform heating performance on the product (Huang et al., 2018), there were many potential improvements of the heating uniformity on the RF development. Dag et al., (2021) experimentally showed that the fluid

immersion of soybean oil could improve the RF heating uniformity of corn flour, but the mechanism was not clear. Besides, the non-uniform heating also results in the quality and functionality change in flour, and less study focuses on the quality change of low moisture food under RF treatment.

In this study, we will use Multiphysics-based computer simulation to evaluate the effect of immersion fluids on RF heating performance of the corn flour sample. We will also investigate the quality and functionality change of bleached and unbleached all-purposed flour after RF-assisted pasteurization.

References

Archer, J., Jervis, E.T., Bird, J., Gaze, J.E., 1998. Heat resistance of Salmonella weltevreden in low-moisture environments. J. Food Prot. https://doi.org/10.4315/0362-028X-61.8.969

Boreddy, S.R., Birla, S., Froning, G., Thippareddi, H., Subbiah, J., 2014. Effect of Radio Frequency Assisted Thermal Processing on Quality and Functional Properties of Egg White Powder. Trans. ASABE 57, 1761–1770. https://doi.org/10.13031/trans.57.10781

CAC (Codex Alimentarius Commision), 2015. CODE OF HYGIENIC PRACTICE FOR LOW-MOISTURE FOODS.

CDC, 2018. Multistate Outbreak of Salmonella Typhimurium Infections Linked to Dried Coconut | March 2018 | Salmonella | CDC [WWW Document]. URL https://www.cdc.gov/salmonella/typhimurium-03-18/index.html (accessed 1.30.21).

CDC, 2012. Salmonella Bredeney Infections Linked to Peanut Butter [WWW Document]. URL https://www.cdc.gov/salmonella/bredeney-09-12/index.html (accessed 1.30.21).

Dag, D., Singh, R.K., Kong, F., 2021. Effect of immersion medium on radio frequency (RF) heating uniformity of corn flour. J. Food Eng. under Revis.

Finn, S., Condell, O., McClure, P., Amézquita, A., Fanning, S., 2013. Mechanisms of survival, responses, and sources of salmonella in low-moisture environments. Front. Microbiol. 4. https://doi.org/10.3389/fmicb.2013.00331

Gao, M., Tang, J., Wang, Y., Powers, J., Wang, S., 2010. Almond quality as influenced by radio frequency heat treatments for disinfestation. Postharvest Biol. Technol. 58, 225–231. https://doi.org/10.1016/j.postharvbio.2010.06.005

Hu, S., Zhao, Y., Hayouka, Z., Wang, D., Jiao, S., 2018. Inactivation kinetics for Salmonella typhimurium in red pepper powders treated by radio frequency heating. Food Control. https://doi.org/10.1016/j.foodcont.2017.10.034

Huang, Z., Marra, F., Subbiah, J., Wang, S., 2018. Critical Reviews in Food Science and Nutrition Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review. https://doi.org/10.1080/10408398.2016.1253000

Jiang, H., Gu, Y., Gou, M., Xia, T., Wang, S., 2020. Radio frequency pasteurization and disinfestation techniques applied on low-moisture foods. Crit. Rev. Food Sci. Nutr. https://doi.org/10.1080/10408398.2019.1573415

Li, Y.C., Chen, S. Der, Yao, M.C., 2015. Effects of radio frequency heating on disinfestation and sterilization of rice flour. Taiwan. J. Agric. Chem. Food Sci. https://doi.org/10.6578/TJACFS.2015.014

Liu, S., Ozturk, S., Xu, J., Kong, F., Gray, P., Zhu, M.J., Sablani, S.S., Tang, J., 2018. Microbial validation of radio frequency pasteurization of wheat flour by inoculated pack studies. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2017.08.013

Los, A., Ziuzina, D., Bourke, P., 2018. Current and Future Technologies for Microbiological Decontamination of Cereal Grains. J. Food Sci. https://doi.org/10.1111/1750-3841.14181

Ozturk, S., Kong, F., Singh, R.K., Kuzy, J.D., Li, C., 2017. Radio frequency heating of corn flour: Heating rate and uniformity. https://doi.org/10.1016/j.ifset.2017.05.001

Piyasena, P., Dussault, C., Koutchma, T., Ramaswamy, H.S., Awuah, G.B., 2003. Radio Frequency Heating of Foods: Principles, Applications and Related Properties - A Review. Crit. Rev. Food Sci. Nutr. https://doi.org/10.1080/10408690390251129

Ran, X. li, Zhang, M., Wang, Y., Liu, Y., 2019. Vacuum radio frequency drying: a novel method to improve the main qualities of chicken powders. J. Food Sci. Technol. 56, 4482–4491. https://doi.org/10.1007/s13197-019-03933-0

U.S. Food & Drug., 2019. Hometown Food Company Recalls Two Production LOT Codes of Pillsbury® Unbleached All-Purpose 5lb Flour Due to Possible Health Risk | FDA [WWW Document]. URL https://www.fda.gov/safety/recalls-market-withdrawals-safety-alerts/hometown-food-company-recalls-two-production-lot-codes-pillsburyr-unbleached-all-purpose-5lb-flour (accessed 1.30.21).

Wang, Y., Zhang, L., Johnson, J., Gao, M., Tang, J., Powers, J.R., Wang, S., 2013. Developing Hot Air-Assisted Radio Frequency Drying for In-shell Macadamia Nuts. Food Bioprocess Technol. 7, 278–288. https://doi.org/10.1007/s11947-013-1055-2

Yu, D.U., Shrestha, B.L., Baik, O.D., 2015. Radio frequency dielectric properties of bulk canola seeds under different temperatures, moisture contents, and frequencies for feasibility of radio frequency disinfestation. Int. J. Food Prop. https://doi.org/10.1080/10942912.2015.1013630

Zheng, A., Zhang, B., Zhou, L., Wang, S., 2016. Application of radio frequency pasteurization to corn (Zea mays L.): Heating uniformity improvement and quality stability evaluation. J. Stored Prod. Res. https://doi.org/10.1016/j.jspr.2016.04.007

Zhou, L., Wang, S., 2016. Industrial-scale radio frequency treatments to control Sitophilus

oryzae in rough, brown, and milled rice. https://doi.org/10.1016/j.jspr.2016.03.002

Zhu, H. kun, Yang, L., Fang, X. fa, Wang, Y., Li, D., Wang, L. jun, 2021. Effects of intermittent radio frequency drying on structure and gelatinization properties of native potato flour. Food Res. Int. 139, 109807. https://doi.org/10.1016/j.foodres.2020.109807

Chapter 2

Modeling the Effect of Immersion Fluids on the Radiofrequency Heating Performance of Corn Flour

This chapter has been submitted to the Journal of Food Science (JFS) and it is under review right now.

Abstract

Non-uniform heating is a significant challenge in radiofrequency (RF) heating for pasteurizing low moisture foods. Previous experiments showed that the immersion of fluids could change the RF heating uniformity and rate of corn flour without knowing clear mechanisms. This study developed a finite-element-based model that incorporated quasi-static electromagnetics and Fourier's heat transfer to understand the effect of immersion fluids (air, soybean oil, and deionized water) on the RF heating performance of corn flour. The model was validated by and showed good agreement with experimental thermal images. The simulation results showed that the immersion of soybean oil increased the average heating rate and improved the heating uniformity compared to immersions of air and deionized water. Less distortion of electric potential reduced the fringe effect of edge heating. The higher heating rate was attributed to more dissipated power and less surface heat loss. The use of soybean oil as immersion fluid could be a promising strategy to be implemented with RF technology to improve heating performance and food safety of low moisture food products.

2.1 Introduction

Even though the low moisture food is a strict environment for the pathogen microbes to grow, many *Salmonella* outbreak in low moisture food products had warn the possibility of food contamination during harvest, processing, or transportation (CDC, 2018, 2012; U.S. Food & Drug., 2019) (Ozturk et al., 2017). Therefore, it is necessary to find a promising method to pasteurize the low moisture food and prevent the food safety problem. Thermal treatment is a good choice, but the conventional thermal treatment usually has low heating efficiency on the low moisture food, since its low thermal conductivity. To increase the heating rate and improve the heating uniformity, radiofrequency (RF) treatment is a promising pasteurization treatment (Boreddy et al., 2014). As a volumetric heating, the heat source can be generated inside of the food to heat faster and more evenly. Accoding to Jiang et al. (2020), many research on low moisture food thermal treatment used the RF technology showed the successfulness. Although with great promise, non-uniform heating is still a challenge in RF processing. Huang et al. (2018) thoroughly reviewed the non-uniform RF heating of a variety of food products, including low moisture foods. The non-uniformity of the RF heating was attributed to several factors, mainly including the design of RF systems (such as the inductance positions, feeding strips, electrode shape, and electrode configuration) and the property and geometry of the treated sample (dielectric and thermal properties, surrounding media, packaging geometries, and the sample position in the RF oven). Several approaches have been proposed to modify the RF system for improving the heating uniformity of low moisture foods. Gao et al. (2011) circulated hot air (55 °C) in a pilot-scale RF system to pasteurize the almond and achieved better heating uniformity. Wang et al.

(2005) and Chen et al. (2015) reported that the intermittent mixing/stirring added in the RF heating process could improve the heating uniformity of in-shell walnuts and wheat kernels samples, respectively. Tiwari et al. (2011) reported that the bending of the top electrode to specific positions and angles could be used to improve the heating uniformity for a particular sample size. Although modifying the RF system showed potential to improve heating uniformity, these approaches can only be used for specific food applications. For example, adding hot air circulation and stirred/mixing may only be good for granule products, such as nuts and grains; the bending of the top electrode may need to be adjusted to fit for products with different shapes and sizes.

In addition to these approaches of modifying the RF systems, several approaches of modifying the treatment samples have been studied and showed success. Jiao et al. (2014) developed an approach of using polyetherimide (PEI) as a surrounding material around a jar of peanut butter to improve the heating uniformity of peanut butter. In this study, the PEI has a closer dielectric constant to peanut butter, which guided the electric field distribution inside the products, reduced the overheat spot, and improved the temperature distribution. Huang et al. (2016) used a similar approach to apply on soybean flour with the polystyrene container (closer dielectric constant to soybean flour) and found a decrease in maximum/minimum temperature difference and improvement in uniformity. Zhang et al., (2017) and Jiao et al. (2015) also showed that the use of polypropylene and PEI blocks, respectively, around large block geometry could improve heating uniformity. In these studies, multiphysics models were developed to understand the RF heating process and found that the surrounding materials can guide the electric field to distribute more evenly since similar dielectric properties between

food and surrounding material. Besides, a higher heating rate was observed for the samples with surrounding materials. The higher heating rate was attributed to the increased dielectric material volume, which improved the impedance match between the load circuit and the tank circuit (Jiao et al., 2014).

It is noted that PEI and polypropylene are rigid materials, which may not be flexible to be applied in the food industry to accommodate products with different shapes and sizes. To improve the flexibility of the surrounding materials, Dag et al., (2021) used liquid materials in their experiments and comprehensively evaluated the effect of surrounding materials (soybean oil, deionized water, and air), surrounding material levels, heating model (stationary vs movement), electrode gap, and heating time on the RF heating performance of corn flour. The experimental results showed that the soybean oil could improve the heating rate and uniformity of corn flour. However, the effect of surrounding materials on the RF heating performance can only be superficially understood from the temperature observations without knowing the mechanisms that cause the improved heating uniformity and heating rate. It is necessary to perform a thorough evaluation using analytical approach to reveal the mechanisms to further develop the immersion fluids approach. Multiphysics-based computer simulation can be used as an efficient approach to comprehensively understand the effect of different immersion fluids on the RF heating performance and mechanisms.

Therefore, the objectives of this study are to:

1) develop and validate a finite-element-based model to simulate the RF heating of corn flour immersed in various fluids (air, soybean oil, and deionized water); and

2) use the validated models to understand the effect of different immersion fluids on the

RF heating performance (temperature distribution, heating rate, and heating uniformity) and their mechanisms.

2.2 Materials and methods

2.2.1 RF system and food samples

A 6 kW, 27.12 MHz pilot-scale free-running oscillator RF system (COMBI 6-S, Strayfield International, Wokingham, UK) was used in the study. The corn flour sample (288 g) was fully filled and compressed in a polypropylene tray (Rubber Maid, 320 mL filled). The polypropylene tray was settled at 12 mm upper to the bottom of a Pyrex glass container (Outer diameter: 170 mm; wall thickness: 2.4 mm; height: 90 mm), which was fully filled with different immersion fluids (air, deionized water, and soybean oil). This 12 mm space between the bottom of the polypropylene tray and glass container was included in the model to mimic the experiments that a chopstick (not included in the model) was used to support the polypropylene tray bottom. The immersion of air was used as a control treatment where the glass container was also included in both modeling and experiments and thus the air can be considered as an immersion fluid; soybean oil was selected because its dielectric constant is close to the dielectric constant of the corn flour sample; water was selected because it is a common fluid and was used as a comparison.

2.2.2 Model development

2.2.2.1 Model geometry

The RF system geometry included a chamber with a metallic enclosure wall and the top and bottom parallel-plate electrodes. The electrode gap between top and bottom electrodes

was set as 110 mm. The whole sample included a cylindrical glass container, filled immersion fluid, a polypropylene tray, and the corn flour inside the polypropylene tray. The whole sample was placed at the center of the bottom electrode. The schematic views of the RF system and sample geometry used in the model were shown in Figure 2.1.

2.2.2.2 Model assumption

In this study, the following assumptions were made to simplify the model:

(1) Due to the little change in deionized water and relatively high viscosity of soybean oil, the immersion fluids were assumed static without movement during the RF heating process.

(2) Some details of the tray geometry (i.e., irregular plastic tray cap) were not included in the model to reduce the computation complexity.

(3) The corn flour sample was assumed to be uniformly compressed, although the plastic tray cap has uneven surface.

(4) The moisture evaporation in the corn flour sample during the RF heating was ignored and not incorporated in the model.

(5) Some properties of materials were assumed as constant or linear change with temperature increase, as discussed in the 2.2.2.5 material properties section.

2.2.2.3 Governing equation

The electric field distribution in the RF system is governed by Maxwell's equation. Since the wavelength (11 m) of the 27.12 MHz RF system is much larger than the electrode plates (0.4×0.83 m^2), the wave propagation can be neglected to simplify Maxwell's equation to the Laplace equation with the quasi-static assumption (Choi and Konrad, 1991):

$$-\nabla \cdot \left((\sigma + j2\pi f \varepsilon_0 \varepsilon_m)\nabla \mathrm{V}\right) = 0 \quad (1)$$

where σ is the electrical conductivity (S•m^{-1}), $j = \sqrt{-1}$ is the imaginary number, f is the frequency (27.12 MHz), ε_0 is the permittivity of free space (8.86 ×10 $^{-12}$ F•m^{-1}), ε_m is the complex relative permittivity which can be expressed in terms of dielectric constant ε_m' and loss factor ε_m'' ($\varepsilon_m = \varepsilon_m' - j\varepsilon_m''$), and V is the electric potential between top and bottom electrode (V).

The electric field **E** (V•m^{-1}) can be calculated as:

$$\boldsymbol{E} = -\nabla V \quad (2)$$

The dissipated power P (W) converted from the electromagnetic energy in the sample can be calculated as (Datta, 2001):

$$P = 2\pi f \varepsilon_0 \varepsilon_m'' {E_{rms}}^2 = \pi f \varepsilon_0 \varepsilon_m'' |E|^2 \quad (3)$$

where E_{rms} is the root mean square value of the electric field.

The generated thermal energy power is then used in the heat transfer process. The heat transfer was only considered in the sample domains, including corn flour, polypropylene tray, immersion fluids, and glass container. The heat transfer process is simulated by the Fourier's equation (Uyar et al., 2015) ignoring the heat convection in the immersion fluids:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \mathrm{P} \quad (4)$$

where $\frac{\partial T}{\partial t}$ represents the heating rate (°C•min^{-1}), ρ is the density (kg•m^{-3}), C_p is the specific heat capacity (J•kg^{-1}•K^{-1}), and k is the thermal conductivity (W•m^{-1}•K^{-1}).

2.2.2.4 Boundary and initial conditions

The voltage of the top electrode is an important boundary condition in the RF simulation. In previous studies, the voltage was typically estimated by using an analytical

approach based on experimental results using equation (Birla et al., 2008):

$$V = (d_{air}\sqrt{\varepsilon'^2 + \varepsilon''^2}) + d_{mat})\sqrt{\frac{\rho C_p}{\pi f \varepsilon_0 \varepsilon''}\frac{\partial T}{\partial t}} \quad (5)$$

where $d_{air}$and d_{mat} are air gap and material thicknesses (m), and the $\frac{\partial T}{\partial t}$ is the average heating rate of the sample determined from the experiments. However, in this study, the average heating rate of the sample was not able to be determined because the average temperature of multiple materials (corn flour, polypropylene tray, immersion fluids, and glass container) cannot be obtained accurately from experiments. Thus, this study first swept top electrode voltage values in the simulations to determine voltage values that make a good match of spatial temperature on the top surface of the corn flour sample between simulation and experiment (Jiao et al., 2014). Then the spatial temperature at the central slice was compared between simulation and experiment to validate the model accuracy. Based on the experimental validation, the top electrode voltage values were determined as 9300, 6400, and 9100 V for the immersion scenarios of air, soybean oil, and water, respectively. The bottom electrode and all the metal shielding parts were set as the ground boundaries ($V = 0$). The convective heat transfer occurs at the outside surface of the glass containers and the top surface of the immersion fluids. These surfaces exposed to outside air at 20.8 °C. The natural convective heat transfer coefficient (h) was set as 5 W•m^{-2}•K^{-1}(Chen et al., 2019).

The initial temperature of the heat transfer domains was set at 21.7 °C.

2.2.2.5 Material properties

The density of the compressed corn flour in the tray was calculated as 288 g / 320 mL = 900 kg•m^{-3}. The thermal conductivity of corn flour was calculated as 0.176 W•m^{-1}•K^{-1} at density of 900 kg•m^{-3} from the reported value of 0.113 W•m^{-1}•K^{-1} which was measured at the

density of 526 kg•m^{-3} from Ozturk et al. (2017). The specific heat capacity of 2.12 kJ•kg^{-1}•K^{-1} reported from Ozturk et al. (2017) was used in the model. The dielectric properties at this density were calculated by using the reported properties at 526 kg•m^{-3} (Ozturk et al., 2017) following the Complex Refractive Index mixture equation (Liu et al., 2009):

$$\sqrt{\varepsilon} = v_1\sqrt{\varepsilon_1} + v_2\sqrt{\varepsilon_2} \quad (6)$$

where ε are the dielectric properties of corn flour at low density (526 kg•m^{-3}), ε_1 are the dielectric properties at high density (900 kg•m^{-3}), ε_2 are the dielectric properties of air (1 - j×0), v_1 (0.58) and v_2 (0.42) are the volume fractions of high density corn flour and air, respectively. The calculated dielectric properties of the compressed corn flour sample were $6.62 - \mathrm{j} \times 0.30$ (20℃), and $18.14 - \mathrm{j} \times 1.86$ (80℃). The dielectric properties of both deionized water and corn flour samples were assumed to follow a linear relationship in the temperature range; while all the other materials were assumed to be constant during the RF heating process.

All the model parameters and material properties are summarized in Table 2.1.

2.2.2.6 Simulation strategy

The simulation was performed in the commercial finite-element based software, COMSOL 5.5a. The mesh of the whole geometry was discretized as tetrahedral elements. The mesh size was chosen based on a convergence study when the maximum temperature between successive calculations was less than 0.1% (Jiao et al., 2014). The total mesh included 1,064,019 domain elements, 65,946 boundary elements, and 2,480 edge elements. The mesh of the RF system cavity and the whole corn flour product was shown in Figure 2.2. A time-dependent fully coupled MUMPS solver with an initial time step of 0.06 s was used in

the simulation.

The model was performed on a computer workstation with a 128 GB RAM operating memory running on two 16-core Intel(R) Xeon(R) 3.20 GHz wavenumber. The typical simulation time cost about 30 min.

2.2.3 Model validation

The model was validated by comparing with the reported experimental results of the RF heating of corn flour Dag et al., (2021). Corn flour samples were heated in the RF system for 5 min at the stationary condition (without movement) with an electrode gap of 11 cm surrounded with three fluids of air, deionized water, and soybean oil. The top and middle layers of the spatial temperature profiles after heating were recorded by a thermal imaging camera (FLIR T440, FLIR Systems, Inc., North Billerica, 116 MA, USA) and compared the heating pattern and maximum temperature at the top surface of the corn flour sample with simulation results for model validation.

2.2.4 Data analysis

The simulated RF heating performance (temperature distribution, heating rate, and heating uniformity) of corn flour were evaluated. The average temperature ($\bar{T}$) of corn flour during the RF heating process was evaluated to determine the average heating rate. The uniformity index (λ) of corn flour during RF heating were calculated as (Wang et al., 2007):

$$\lambda = \frac{\Delta\sigma}{\Delta\bar{T}} \tag{7}$$

where $\Delta\sigma$ is the rise of standard deviation during the RF heating, the $\Delta\bar{T}$ is the rise of average temperature during heating. The lower uniformity index indicates better heating uniformity. To understand the mechanism that caused different heating performances, the

electric potential, electric field distribution, and electric power density were evaluated.

2.3 Results and discussion

2.3.1 Model validation

The simulated and experimental temperature profiles at the top and middle layers of the corn flour with different immersion fluids (air, soybean oil, and deionized water) after 5 min RF heating are shown in Figure 2.3. Generally, the simulated heating patterns for both the top and middle slices of temperature profiles of cornflour sample showed good agreement with the experimental results, but the exact temperature predictions showed considerable differences, especially for the central regions at both the top and middle layers. The models successfully predicted the heating patterns and trends for three immersion conditions. From the top and middle slices of temperature profiles, the corn flour immersed in soybean oil was heated more than that in air and following with that in water.

The corn flour samples immersed in air and soybean oil were heated more at the edges and less at the central areas for both top and middle layers. The predicted maximum temperatures fell within the experimental temperature variations of three replications, while the simulated minimum temperature was lower than the experimental results at the cold spots. The heating patterns were similar to the previously reported RF heating of low moisture food products of wheat kernels (Chen et al., 2017), egg white powders (Chen et al., 2019), whole milk powder (Dag et al., 2019) and peanut butter (Jiao et al., 2014) surrounded with air. The corn flour samples immersed in water showed different heating pattern than those immersed in air and soybean oil. As shown in Figure 2.3, both the experimental and simulated heating

profiles for the corn flour immersed in water showed hot spots in the central area and cold spots at the edges for both top and middle layers. A similar result was reported in Birla et al., (2008) that the surrounding water changed the hot spots from the edges to the center of the samples during the RF heating of model fruit. However, the predicted temperature at the middle layer in this study was about (5 to 7 °C) higher than the experimental results, while matching the top layers between experiment and simulation.

The discrepancy between simulated and experimental results might be attributed to that some experimental details were not able to be incorporated in the models. The experiments used a highly compacted corn flour sample (average bulk density of 900 $kg \cdot m^{-3}$) in the polypropylene tray whose tray lid is neither flat nor in a regular shape, which compressed the sample non-uniformly throughout the whole tray. As shown in Figure 2.4, in the experiments, the corn flour around the center region was compressed more, which lead to higher density and dielectric properties in that region. Therefore, the experimental thermal images at the center region for the immersion of air and deionized water were higher than the simulated results when matching the hot spots of edges.

For the immersion of deionized water, the hot spots were at the center region where the density might be higher than the average bulk density (900 $kg \cdot m^{-3}$) in the simulation. In order to match the top layer temperature between simulation and experiments, the estimated top electrode voltage was higher than it supposed to be. In order to confirm this assumption, 200 g corn flour was filled to the container at 296 mL level, immersed in the deionized water, and without sever lid compression (average bulk density of 675.7 $kg \cdot m^{-3}$) was simulated and compared to the experimental results at same condition. As shown in Figure 2.5, the predicted

temperature at the middle layer was reduced significantly and matched closely with the experimental results.

2.3.2 Effect of immersion fluids on the heating pattern

As shown in Figure 2.3, the immersion of soybean oil showed a similar heating pattern to that of air, where edge heating was observed, while the immersion of water significantly changed the heating profiles, where the central area was heated more. The distinct heating pattern caused by the immersion fluids could also be clearly observed from the vertical central slices in the corn flour samples, as shown in Figure 2.6. At the beginning of the RF heating (from t = 0 to 1 min), the heating patterns were not clear due to the little temperature change. After 3 minutes of heating, edge heating was clearly shown in the samples immersed in air and soybean oil. The sample immersed in water was heated relatively more at the center of the whole tray of corn flour samples compared to other locations after 5 minutes.

The distinct heating patterns among samples immersed in different fluids may be explained by the electric potential and electric field directions. Figure 2.7 showed the electric potential (contour plot) from the top to the bottom electrodes of the RF system and the electric field directions (arrow plot) inside the fluids and corn flour samples during the RF heating process. At the beginning of the RF heating, the electric potential for scenarios of air was almost uniformly distributed within air domains between the top and bottom electrodes, while distortion of voltage distribution was observed within the corn flour domain. The top edges of the corn flour samples had higher electric potential (~ 3500 V) than the top central region (~ 3000 V), which caused the distortion of the electric field (arrows point from the edges to the central region). For the corn flour samples immersed in soybean oil, the

distortion of electric potential distribution was reduced slightly when compared to that immersed in air, where the electric potential difference between edge and center was less than 500 V. The reduced electric potential difference might be due to the similar dielectric properties between soybean oil and corn flour. A similar result was observed in Jiao et al. (2014) that the surrounding of PEI significantly improved the electric potential distribution within the peanut butter samples. Huang et al. (2015) also reported that similar dielectric constant between surrounding materials and food samples could improve the heating uniformity. The immersion of deionized water showed significantly different electric potential distribution than that of air and soybean oil scenarios, where the electric potential decreased significantly from the top electrode (~ 9000 V) to the top of the water (~ 1500 V) in the glass container and then only decreased slightly in the water domain. The low electric potential values within the water domain were due to the much higher dielectric constant of water than that of air above the water, where water is a better capacitance to store electric charges and lower electric potential (James and Dale, 2011; Huang et al., 2018).

The distortion of electric potential distribution influenced the electric field and the temperature distribution within the corn flour samples. According to Eq. 2, the electric field is proportional to the electric potential gradient. Therefore, the electric field directions (arrow plot) pointed from top to the bottom electrodes following the directions of electric potential decrease (contour plot) and did not change much during the heating process, as shown in Figure 2.7. Note that the size of the arrows was uniformly used and did not indicate the magnitude of the electric field strength. Moreover, the electric field directions showed considerable differences among scenarios of various immersion fluids. For the scenarios of

air and soybean oil, the electric field was distorted from the fluid domain to the edges of the corn flour samples; while for the scenario of deionized water, the electric field was distorted from the central area of the water domain (above corn flour sample) to the edges of the water domain (side of corn flour sample). The different distortions of electric potential resulted in different electric potential gradients within corn flour samples.

Furthermore, the electric potential gradient (contour plot in Figure 2.7) resulted in different electric field strength in corn flour samples, as shown in Figure 2.8. The higher electric potential gradient led to higher electric field strengths at the edge of corn flour sample immersed in air and then resulted in more edge heating. The higher electric field strength at the edges was observed as the fringe effect in many other RF heating processes with air as surroundings (Chen et al., 2017; Huang et al., 2016; Lau et al., 2016). The fringe effect was slightly reduced in the corn flour immersed in soybean oil but was not observed in the sample immersed in deionized water, where relatively higher electric field strength was found in the central area of the sample. It also could be observed from Figure 2.8 that the electric field strength decreased in all samples with heating time, which was due to the increasing dielectric properties of corn flour samples (Datta, 2001). However, the electric field distribution patterns did not change much.

2.3.3 Effect of immersion fluids on the heating rate

Besides the heating pattern, the immersion fluids also influenced the RF heating rates of corn flour samples, as shown in Figures 2.3. and 2.6. The immersion of soybean oil increased the maximum temperature from about 58 and 68 °C (air immersion) to about 70 and 76 °C for the top and middle layers, respectively. The immersion of water not only changed the hot

and cold spots in the sample but also significantly reduced the final temperatures by 25 to 35 °C when compared to the immersion of air. The effect of immersion fluids on the RF heating rates could be seen from the average temperature of the corn flour samples, as shown in Figure 2.9. It showed that all the average temperature profiles of corn flour samples immersed in air, water, and soybean oil generally increased with time almost linearly (R^2> 0.99) but with significantly different rates. The slopes of the fitted linear lines (average temperature $\bar{T}$ vs time t) represented the simulated average heating rates of samples. The corn flour sample immersed in soybean oil was heated at the fastest rate of 8.1 °C/min, while the one immersed in water was heated at the slowest rate of 2.7 °C/min. The average heating rate of corn flour immersed in soybean oil is about 44.6% higher than that in air. This increased heating rate was also reported from a previous study that the surrounding of PEI could increase the heating rate from 6.8 to 20.8 °C/min (Jiao et al., 2014). The increased heating rate with surrounded material was considered due to a better impedance match between the load circuit and the tank circuit, which resulted in increased input power (Jiao et al., 2014).

Moreover, the effect of immersion fluids (soybean oil and water) on the heating rates of the corn flour samples could be understood from the previously discussed electric voltage (Figure 2.7.) and the electric field strength (Figure 2.8.), as well as the electric power absorption (Figure 2.10.). As discussed earlier, the sample immersed in soybean oil had a higher electric voltage gradient and electric field strength than other samples. According to Eq. 3, the power absorption within the corn flour sample is proportional to the dielectric loss factor of corn flour and the square of electric field strength. Although the electric field

strength decreased with the heating time shown in Figure 2.8, the power absorption increased with heating time shown in Figure 2.10., which was mainly attributed to the increasing dielectric loss factor of corn flour. Figure 2.10. also clearly showed different power absorption for samples immersed in various fluids where the sample immersed in soybean oil had the highest power absorption while that in deionized water had the lowest value. The contrast power absorption for different immersion scenarios was the dominant factor that influenced the heating rates.

However, it should be observed from Figure 2.11.(a) that the total power absorption within the whole tray of corn flour samples increased with heating time, while the heating rates were relatively constant. The trend difference between total power absorption and average heating rate was mainly attributed to the heat loss from corn flour to the immersion fluids. As shown in Figure 2.11.(b), the integrated surface heat loss for the samples immersed in air and water increased with heating time, while that for the sample immersed in soybean oil increased first and stabilized at relatively lower values. The differences between the total power absorption and the surface heat loss were the effective heat sources for heating the corn flour samples, which resulted in constant heating rates for different scenarios. Figure 2.11.(b) also showed that the surface heat loss for the sample immersed in the air was much higher than that immersed in soybean oil. The ratio of the lost heat power and dissipated power for the immersion of air scenario was up to 14.7% during the heating process, lowering the heating rate significantly. The sample immersed in water also had much more surface heat loss than that immersed in soybean oil due to the higher thermal conductivity of water and the lower deionized water temperature. During the RF heating process, the

deionized water temperature was not increased much (~ 1 °C), while the soybean oil temperature increased by about 35 °C, which were observed from experiments. Although soybean oil has a very low dielectric loss factor, it can be heated by electromagnetic waves (Tan et al., 2001) due to the high electric field strength (because of low dielectric constant) and small specific heat capacity. Therefore, less surface heat loss for the sample immersed in soybean oil also contributed to its higher heating rate considerably.

2.3.4 Effect of immersion fluids on heating uniformity

The effect of immersion fluids on the heating uniformity performances of the samples immersed in different fluids after five minutes of RF heating was summarized in Table 2.2. Among the three scenarios, the sample immersed in the water had the smallest maximum/minimum temperature difference and standard deviation values but the smallest average temperature as well. Thus, the heating uniformity index (calculated as the ratio of the rise of the standard deviation to the rise of average temperature) for the sample immersed in water was much higher than that immersed in soybean oil, indicating worse heating uniformity. When compared to the sample immersed in air, the sample immersed in soybean oil had smaller maximum/minimum temperature difference and standard deviation values, as well as higher average temperature, resulting in better heating uniformity (smaller heating uniformity index).

The improvement of the heating uniformity for the corn flour samples immersed in soybean oil compared to that in the air might be attributed to two reasons. First, the immersion fluid of soybean oil reduced the fringe effect of the electric field in the corn flour samples, as discussed in Sections 3.2 and 3.3. A similar result was reported in Jiao et al.

(2014) that the heating uniformity of peanut butter samples surrounded with Polyetherimide (PEI) was improved where the standard deviation was reduced by about 2 °C. Besides the reduced fringe effect, the increased average temperature rise also influenced the calculated heating uniformity index according to Eq.7. As discussed in Figure 2.5, the average heating rate of the sample immersed in soybean oil was higher than that in the air. This higher rise of the average temperature for the samples immersed in soybean could contribute to the lower heating uniformity index and better heating uniformity.

2.4 Conclusion

A finite-element-based model that incorporated multiphysics of quasi-static electromagnetics and Fourier's heat transfer was developed to simulate the RF heating of corn flour immersed in fluids of air, soybean oil, and deionized water, respectively. The models were validated by comparing the simulated temperature profiles at the top and middle layers of corn flour samples with the experimental results and showed good agreement in the heating pattern and heating performance trend. The effect of immersion fluids on the RF heating performances (heating pattern, heating rate, and heating uniformity) was evaluated, and their mechanisms were comprehensively evaluated. The conclusions of this study are:

- The immersion of soybean oil showed similar heating patterns to the immersion of air, while the immersion of water considerably changed the edge heating pattern to center-focused heating. Due to the little difference of dielectric constant values between corn flour and soybean oil, the immersion of soybean oil reduced the fringe effect of edge heating by reducing the distortion of electric potential at the edges of corn flour sample.

The electric field density and dissipated power distributed more to the central area of the corn flour when compared to the immersion of air.

- A higher electric potential gradient was observed in the corn flour sample that was immersed in soybean oil, which resulted in more dissipated power and thus a higher heating rate than that immersed in air. The increased temperature and low thermal conductivity of soybean oil reduced the surface heat loss from corn flour to surroundings and also contributed to the high heating rate. The corn flour sample immersed in water was heated at a very low heating rate due to the low dissipated power and high heat loss.
- The reduced edge heating and the increased average temperature in the corn flour sample immersed in soybean oil resulted in the best heating uniformity. The use of soybean oil as immersion fluid in the RF heating process could be developed as a promising technology to pasteurize low moisture food products with improved food safety

References

AACC, 2000. Approved Methods of the AACC, in: American Association of Cereal Chemists.

Abdullah, A., Mohamad, I.S., Hashim, A.Y.B., Abdullah, N., Wei, P.B., Isa, M.H., Abidin, S.Z., 2016. Thermal conductivity and viscosity of deionised water and ethylene glycol-based nanofluids. J. Mech. Eng. Sci. ISSN 10, 2249–2261. https://doi.org/10.15282/jmes.10.3.2016.4.0210

AOAC, 2000. AOAC Official Methods 925.10 Solids (Total) and Moisture in Flour. AOAC Off. Methods Anal. 3390.

Arabo, E.Y.M., 2011. Shear and extensional viscosities of hard wheat flour dough using a capillary rheometer. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2010.10.027

Archer, J., Jervis, E.T., Bird, J., Gaze, J.E., 1998. Heat resistance of Salmonella weltevreden in low-moisture environments. J. Food Prot. https://doi.org/10.4315/0362-028X-61.8.969

Baker Pedia, n.d. Solvent Retention Capacity (SRC) | Baking Processes | BAKERpedia [WWW Document]. URL https://bakerpedia.com/processes/solvent-retention-capacity/ (accessed 7.12.21).

Birla, S.L., Wang, S., Tang, J., 2008. Computer simulation of radio frequency heating of model fruit immersed in water. J. Food Eng. 84, 270–280. https://doi.org/10.1016/j.jfoodeng.2007.05.020

Boreddy, S.R., Birla, S., Froning, G., Thippareddi, H., Subbiah, J., 2014. Effect of Radio Frequency Assisted Thermal Processing on Quality and Functional Properties of Egg

White Powder. Trans. ASABE 57, 1761–1770. https://doi.org/10.13031/trans.57.10781

Boreddy, S.R., Rose, D.J., Subbiah, J., 2019. Radiofrequency-Assisted Thermal Processing of Soft Wheat Flour. J. Food Sci. 84, 2528–2536. https://doi.org/10.1111/1750-3841.14767

Bosmans, G.M., Peene, L.J., Van Haesendonck, I., Brijs, K., Delcour, J.A., 2019. Impact of chlorine treatment on properties of wheat flour and its components in the presence of sucrose. Food Chem. 274, 434–443. https://doi.org/10.1016/j.foodchem.2018.09.019

Byrd-Bredbenner, C., Abbot, J.M., Wheatley, V., Schaffner, D., Bruhn, C., Blalock, L., 2008. Risky Eating Behaviors of Young Adults-Implications for Food Safety Education. J. Am. Diet. Assoc. https://doi.org/10.1016/j.jada.2007.12.013

CAC (Codex Alimentarius Commision), 2015. CODE OF HYGIENIC PRACTICE FOR LOW-MOISTURE FOODS.

Carter, B.P., Morris, C.F., Anderson, J.A., 1999. Optimizing the SDS sedimentation test for end-use quality selection in a soft white and club wheat breeding program. Cereal Chem. 76, 907–911. https://doi.org/10.1094/CCHEM.1999.76.6.907

CDC, 2021. Say No to Raw Dough [WWW Document]. URL https://www.cdc.gov/foodsafety/communication/no-raw-dough.html (accessed 6.10.21).

CDC, 2018. Multistate Outbreak of Salmonella Typhimurium Infections Linked to Dried Coconut | March 2018 | Salmonella | CDC [WWW Document]. URL https://www.cdc.gov/salmonella/typhimurium-03-18/index.html (accessed 1.30.21).

CDC, 2012. Salmonella Bredeney Infections Linked to Peanut Butter [WWW Document]. URL https://www.cdc.gov/salmonella/bredeney-09-12/index.html (accessed 1.30.21).

Chandrasekaran, S., Ramanathan, S., Basak, T., 2013. Microwave food processing - a review.

Food Res. Int. 52, 243–261. https://doi.org/10.1016/j.foodres.2013.02.033

Chen, J., Lau, S.K., Boreddy, S.R., Subbiah, J., 2019. Modeling of radio frequency heating of egg white powder continuously moving on a conveyor belt. J. Food Eng. 262, 109–120. https://doi.org/10.1016/J.JFOODENG.2019.05.029

Chen, J., Lau, S.K., Chen, L., Wang, S., Subbiah, J., 2017. Modeling radio frequency heating of food moving on a conveyor belt. Food Bioprod. Process. 102, 307–319. https://doi.org/10.1016/j.fbp.2017.01.009

Chen, L., Wang, K., Li, W., Wang, S., 2015. A strategy to simulate radio frequency heating under mixing conditions. Comput. Electron. Agric. 118, 100–110. https://doi.org/10.1016/j.compag.2015.08.025

Choi, C.T.M., Konrad, A., 1991. Finite element modeling of the rf heating process. IEEE Trans. Magn. https://doi.org/10.1109/20.105034

Choi Y, Okos, M.R., 1986. Physical and chemical properties of food. ASAE Publ.

Colombo, A., Pérez, G.T., Ribotta, P.D., León, A.E., 2008. A comparative study of physicochemical tests for quality prediction of Argentine wheat flours used as corrector flours and for cookie production. J. Cereal Sci. 48, 775–780. https://doi.org/10.1016/j.jcs.2008.05.003

Cruse, P., 2014. Introduction to Colour Models ('Spaces') [WWW Document]. Berkhamsted, United Kingdom Graph. Qual. Consult. . URL http://www.colourphil.co.uk/lab_lch_colour_space.shtml (accessed 6.13.21).

Dag, D., Singh, R.K., Kong, F., 2021. Effect of immersion medium on radio frequency (RF) heating uniformity of corn flour. J. Food Eng. under Revis.

Dag, D., Singh, R.K., Kong, F., 2019. Dielectric properties, effect of geometry, and quality changes of whole, nonfat milk powder and their mixtures associated with radio frequency heating. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2019.04.017

Datta, A.K., 2001. Handbook of Microwave Technology for Food Application, Handbook of Microwave Technology for Food Application. https://doi.org/10.1201/9781482270778

DICK, J., JW, D., JS, Q., 1983. A MODIFIED SCREENING TEST FOR RAPID ESTIMATION OF GLUTEN STRENGTH IN EARLY-GENERATION DURUM WHEAT BREEDING LINES. A Modif. Screen. TEST RAPID Estim. GLUTEN STRENGTH EARLY-GENERATION DURUM WHEAT Breed. LINES.

Dodier, D., 2015. Comparative Study Of The D-values of Salmonella spp. and Enterococcus faecium in Wheat Flour.

Ee, K.Y., Eng, M.K., Lee, M.L., 2020. Physicochemical, thermal and rheological properties of commercial wheat flours and corresponding starches. Food Sci. Technol. 40, 51–59. https://doi.org/10.1590/fst.39718

Eglezos, S., 2010. Microbiological quality of wheat grain and flour from two mills in Queensland, Australia. J. Food Prot. 73, 1533–1536. https://doi.org/10.4315/0362-028X-73.8.1533

Fasina, O.O., Colley, Z., 2008. Viscosity and specific heat of vegetable oils as a function of temperature: 35°C to 180°C. Int. J. Food Prop. https://doi.org/10.1080/10942910701586273

Fernandez-Avila, C., Gutierrez-Merida, C., Trujillo, A.J., 2017. Physicochemical and sensory characteristics of a UHT milk-based product enriched with conjugated linoleic acid

emulsified by Ultra-High Pressure Homogenization. Innov. Food Sci. Emerg. Technol. 39, 275–283. https://doi.org/10.1016/j.ifset.2017.01.001

Finn, S., Condell, O., McClure, P., Amézquita, A., Fanning, S., 2013. Mechanisms of survival, responses, and sources of salmonella in low-moisture environments. Front. Microbiol. 4. https://doi.org/10.3389/fmicb.2013.00331

Finnie, S.M., Bettge, A.D., Morris, C.F., 2006. Influence of flour chlorination and ingredient formulation on the quality attributes of pancakes. Cereal Chem. 83, 684–691. https://doi.org/10.1094/CC-83-0684

Gao, M., Tang, J., Villa-Rojas, R., Wang, Y., Wang, S., 2011. Pasteurization process development for controlling Salmonella in in-shell almonds using radio frequency energy. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2010.12.021

Gao, M., Tang, J., Wang, Y., Powers, J., Wang, S., 2010. Almond quality as influenced by radio frequency heat treatments for disinfestation. Postharvest Biol. Technol. 58, 225–231. https://doi.org/10.1016/j.postharvbio.2010.06.005

Guttieri, M.J., Becker, C., Souza, E.J., 2004. Application of Wheat Meal Solvent Retention Capacity Tests Within Soft Wheat Breeding Populations. Cereal Chem. 81, 261–266. https://doi.org/10.1094/CCHEM.2004.81.2.261

Haynes, L.C., Bettge, A.D., Slade, L., 2009. Soft wheat and flour products methods review: Solvent retention capacity equation correction. Cereal Foods World. https://doi.org/10.1094/CFW-54-4-0174

Hu, S., Zhao, Y., Hayouka, Z., Wang, D., Jiao, S., 2018. Inactivation kinetics for Salmonella typhimurium in red pepper powders treated by radio frequency heating. Food Control.

https://doi.org/10.1016/j.foodcont.2017.10.034

Huang, Z., Marra, F., Subbiah, J., Wang, S., 2018a. Critical Reviews in Food Science and Nutrition Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review. https://doi.org/10.1080/10408398.2016.1253000

Huang, Z., Marra, F., Subbiah, J., Wang, S., 2018b. Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review. Crit. Rev. Food Sci. Nutr. https://doi.org/10.1080/10408398.2016.1253000

Huang, Z., Zhang, B., Marra, F., Wang, S., 2016. Computational modelling of the impact of polystyrene containers on radio frequency heating uniformity improvement for dried soybeans. Innov. Food Sci. Emerg. Technol. https://doi.org/10.1016/j.ifset.2015.11.022

Huang, Z., Zhu, H., Yan, R., Wang, S., 2015. Simulation and prediction of radio frequency heating in dry soybeans. Biosyst. Eng. 129, 34–47. https://doi.org/10.1016/j.biosystemseng.2014.09.014

Inoue, C., Hagura, Y., Ishikawa, M., Suzuki, K., 2002. The dielectric property of soybean oil in deep-fat frying and the effect of frequency. J. Food Sci. https://doi.org/10.1111/j.1365-2621.2002.tb09464.x

James, L., Dale, S., 2011. Adhesives Technology for Electronic Applications, Adhesives Technology for Electronic Applications. Elsevier Inc. https://doi.org/10.1016/C2009-0-64364-6

Jiang, H., Gu, Y., Gou, M., Xia, T., Wang, S., 2020. Radio frequency pasteurization and

disinfestation techniques applied on low-moisture foods. Crit. Rev. Food Sci. Nutr. https://doi.org/10.1080/10408398.2019.1573415

Jiao, Y., Shi, H., Tang, J., Li, F., Wang, S., 2015. Improvement of radio frequency (RF) heating uniformity on low moisture foods with Polyetherimide (PEI) blocks. Food Res. Int. https://doi.org/10.1016/j.foodres.2015.04.016

Jiao, Y., Tang, J., Wang, S., 2014. A new strategy to improve heating uniformity of low moisture foods in radio frequency treatment for pathogen control. J. Food Eng. 141, 128–138. https://doi.org/10.1016/j.jfoodeng.2014.05.022

Kim, W., Choi, S.G., Kerr, W.L., Johnson, J.W., Gaines, C.S., 2004. Effect of heating temperature on particle size distribution in hard and soft wheat flour. J. Cereal Sci. 40, 9–16. https://doi.org/10.1016/j.jcs.2004.04.005

Kumar, P., Yadava, R.K., Gollen, B., Kumar, S., Kant Verma, R., Yadav, S., 2011. Nutritional Contents and Medicinal Properties of Wheat: A Review, Life Sciences and Medicine Research.

Kweon, M., Slade, L., Levine, H., 2011. Solvent retention capacity (SRC) testing of wheat flour: Principles and value in predicting flour functionality in different wheat-based food processes and in wheat breeding-A review. Cereal Chem. https://doi.org/10.1094/CCHEM-07-11-0092

Lau, S.K., Dag, D., Ozturk, S., Kong, F., Subbiah, J., 2020. A comparison between the open-ended coaxial probe method and the parallel plate method for measuring the dielectric properties of low-moisture foods. LWT. https://doi.org/10.1016/j.lwt.2020.109719

Lau, S.K., Thippareddi, H., Jones, D., Negahban, M., Subbiah, J., 2016. Challenges in

Radiofrequency Pasteurization of Shell Eggs: Coagulation Rings. J. Food Sci. 81, E2492–E2502. https://doi.org/10.1111/1750-3841.13440

Li, Y.C., Chen, S. Der, Yao, M.C., 2015. Effects of radio frequency heating on disinfestation and sterilization of rice flour. Taiwan. J. Agric. Chem. Food Sci. https://doi.org/10.6578/TJACFS.2015.014

Liu, S., Ozturk, S., Xu, J., Kong, F., Gray, P., Zhu, M.J., Sablani, S.S., Tang, J., 2018. Microbial validation of radio frequency pasteurization of wheat flour by inoculated pack studies. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2017.08.013

Liu, Y., Tang, J., Mao, Z., 2009. Analysis of bread dielectric properties using mixture equations. J. Food Eng. 93, 72–79. https://doi.org/10.1016/j.jfoodeng.2008.12.032

Los, A., Ziuzina, D., Bourke, P., 2018. Current and Future Technologies for Microbiological Decontamination of Cereal Grains. J. Food Sci. https://doi.org/10.1111/1750-3841.14181

McCormick, K.M., Panozzo, J.F., Hong, S.H., 1991. A swelling power test for selecting potential noodle quality wheats. Aust. J. Agric. Res. 42, 317–323. https://doi.org/10.1071/AR9910317

Oh, I.K., Bae, I.Y., Lee, H.G., 2018. Effect of dry heat treatment on physical property and in vitro starch digestibility of high amylose rice starch. Int. J. Biol. Macromol. 108, 568–575. https://doi.org/10.1016/J.IJBIOMAC.2017.11.180

Ozturk, S., Kong, F., Singh, R.K., Kuzy, J.D., Li, C., 2017a. Radio frequency heating of corn flour: Heating rate and uniformity. https://doi.org/10.1016/j.ifset.2017.05.001

Ozturk, S., Kong, F., Singh, R.K., Kuzy, J.D., Li, C., 2017b. Radio frequency heating of corn

flour: Heating rate and uniformity. Innov. Food Sci. Emerg. Technol. 44, 191–201. https://doi.org/10.1016/j.ifset.2017.05.001

Parinyasiri, T., Chen, T.C., Reed, R.J., 1991. YIELDS and BREADING DISPERSION of CHICKEN NUGGETS DURING DEEP-FAT FRYING AS AFFECTED BY PROTEIN CONTENT of BREADING FLOUR. J. Food Process. Preserv. https://doi.org/10.1111/j.1745-4549.1991.tb00179.x

Piyasena, P., Dussault, C., Koutchma, T., Ramaswamy, H.S., Awuah, G.B., 2003. Radio Frequency Heating of Foods: Principles, Applications and Related Properties - A Review. Crit. Rev. Food Sci. Nutr. https://doi.org/10.1080/10408690390251129

Ran, X. li, Zhang, M., Wang, Y., Liu, Y., 2019. Vacuum radio frequency drying: a novel method to improve the main qualities of chicken powders. J. Food Sci. Technol. 56, 4482–4491. https://doi.org/10.1007/s13197-019-03933-0

Saiz, A.I., Manrique, G.D., Fritz, R., 2001. Determination of Benzoyl Peroxide and Benzoic Acid Levels by HPLC during Wheat Flour Bleaching Process. https://doi.org/10.1021/jf9912304

Saka, I., Topcam, H., Son, E., Ozkaya, B., Erdogdu, F., 2021. Effect of radio frequency processing on physical, chemical, rheological and bread-baking properties of white and whole wheat flour. LWT 147, 111563. https://doi.org/10.1016/j.lwt.2021.111563

Schofield, J.D., Bottomley, R.C., Timms, M.F., Booth, M.R., 1983. The effect of heat on wheat gluten and the involvement of sulphydryl-disulphide interchange reactions. J. Cereal Sci. 1, 241–253. https://doi.org/10.1016/S0733-5210(83)80012-5

Senanayake, S., Gunaratne, A., Ranaweera, K., Bamunuarachchi, A., 2013. Effect of Heat

Moisture Treatment Conditions on Swelling Power and Water Soluble Index of Different Cultivars of Sweet Potato (Ipomea batatas (L). Lam) Starch 2013. https://doi.org/10.1155/2013/502457

Slaughter, D.C., Karl H. Norris, William R. Hruschka, 1992. Quality and classification of hard red wheat. Cereal Chem 69, 428–432.

Steertegem, B. Van, Pareyt, B., Slade, L., Levine, H., Brijs, K., Delcour, J.A., 2013a. Impact of Heat Treatment on Wheat Flour Solvent Retention Capacity (SRC) Profiles; Impact of Heat Treatment on Wheat Flour Solvent Retention Capacity (SRC) Profiles. https://doi.org/10.1094/CCHEM-04-13-0069-N

Steertegem, B. Van, Pareyt, B., Slade, L., Levine, H., Brijs, K., Delcour, J.A., 2013b. Impact of Heat Treatment on Wheat Flour Solvent Retention Capacity (SRC) Profiles; Impact of Heat Treatment on Wheat Flour Solvent Retention Capacity (SRC) Profiles. https://doi.org/10.1094/CCHEM-04-13-0069-N

Tan, C.P., Che Man, Y.B., Jinap, S., Yusoff, M.S.A., 2001. Effects of microwave heating on changes in chemical and thermal properties of vegetable oils. JAOCS, J. Am. Oil Chem. Soc. https://doi.org/10.1007/s11745-001-0418-5

Tiwari, G., Wang, S., Tang, J., Birla, S.L., 2011. Analysis of radio frequency (RF) power distribution in dry food materials. J. Food Eng. 104, 548–556. https://doi.org/10.1016/j.jfoodeng.2011.01.015

U.S. Food & Drug., 2019. Hometown Food Company Recalls Two Production LOT Codes of Pillsbury® Unbleached All-Purpose 5lb Flour Due to Possible Health Risk | FDA [WWW Document]. URL https://www.fda.gov/safety/recalls-market-withdrawals-

safety-alerts/hometown-food-company-recalls-two-production-lot-codes-pillsburyr-unbleached-all-purpose-5lb-flour (accessed 1.30.21).

USDA, 2020a. Flour, wheat, all-purpose, unenriched, unbleached [WWW Document]. URL https://fdc.nal.usda.gov/fdc-app.html#/food-details/790018/nutrients (accessed 6.23.21).

USDA, 2020b. Flour, wheat, all-purpose, enriched, bleached [WWW Document]. URL https://fdc.nal.usda.gov/fdc-app.html#/food-details/789890/nutrients (accessed 6.23.21).

USDA, 2017. Flour Tests : USDA ARS [WWW Document]. URL https://www.ars.usda.gov/midwest-area/wooster-oh/corn-soybean-and-wheat-quality-research/docs/flour-tests/ (accessed 6.21.21).

Uyar, R., Bedane, T.F., Erdogdu, F., Koray Palazoglu, T., Farag, K.W., Marra, F., 2015. Radio-frequency thawing of food products - A computational study. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2014.08.018

Vadivambal, R., Jayas, D.S., 2010. Non-uniform temperature distribution during microwave heating of food materials-A review. Food Bioprocess Technol. 3, 161–171. https://doi.org/10.1007/s11947-008-0136-0

VanCauwenberge, J.E., Bothast, R.J., Kwolek, W.F., 1981. Thermal inactivation of eight Salmonella serotypes on dry corn flour. Appl. Environ. Microbiol. 42, 688–691. https://doi.org/10.1128/aem.42.4.688-691.1981

Wang, S., Monzon, M., Johnson, J.A., Mitcham, E.J., Tang, J., 2007. Industrial-scale radio frequency treatments for insect control in walnuts I: Heating uniformity and energy efficiency. Postharvest Biol. Technol. 45, 240–246. https://doi.org/10.1016/j.postharvbio.2006.12.023

Wang, S., Yue, J., Tang, J., Chen, B., 2005. Mathematical modelling of heating uniformity for in-shell walnuts subjected to radio frequency treatments with intermittent stirrings. Postharvest Biol. Technol. 35, 97–107. https://doi.org/10.1016/J.POSTHARVBIO.2004.05.024

Wang, Y., Zhang, L., Johnson, J., Gao, M., Tang, J., Powers, J.R., Wang, S., 2013. Developing Hot Air-Assisted Radio Frequency Drying for In-shell Macadamia Nuts. Food Bioprocess Technol. 7, 278–288. https://doi.org/10.1007/s11947-013-1055-2

Wu, S., Ricke, S.C., Schneider, K.R., Ahn, S., 2017. Food safety hazards associated with ready-to-bake cookie dough and its ingredients. Food Control. https://doi.org/10.1016/j.foodcont.2016.10.010

Xiao, Z.S., Park, S.H., Chung, O.K., Caley, M.S., Seib, P.A., 2006. Solvent retention capacity values in relation to hard winter wheat and flour properties and straight-dough breadmaking quality. Cereal Chem. 83, 465–471. https://doi.org/10.1094/CC-83-0465

Yu, D.U., Shrestha, B.L., Baik, O.D., 2015. Radio frequency dielectric properties of bulk canola seeds under different temperatures, moisture contents, and frequencies for feasibility of radio frequency disinfestation. Int. J. Food Prop. https://doi.org/10.1080/10942912.2015.1013630

Zhang, S., Huang, Z., Wang, S., 2017. Improvement of radio frequency (RF) heating uniformity for peanuts with a new strategy using computational modeling. Innov. Food Sci. Emerg. Technol. https://doi.org/10.1016/j.ifset.2017.02.009

Zheng, A., Zhang, B., Zhou, L., Wang, S., 2016. Application of radio frequency pasteurization to corn (Zea mays L.): Heating uniformity improvement and quality

stability evaluation. J. Stored Prod. Res. https://doi.org/10.1016/j.jspr.2016.04.007

Zhou, L., Wang, S., 2016. Industrial-scale radio frequency treatments to control Sitophilus oryzae in rough, brown, and milled rice. https://doi.org/10.1016/j.jspr.2016.03.002

Zhu, H. kun, Yang, L., Fang, X. fa, Wang, Y., Li, D., Wang, L. jun, 2021. Effects of intermittent radio frequency drying on structure and gelatinization properties of native potato flour. Food Res. Int. 139, 109807. https://doi.org/10.1016/j.foodres.2020.109807

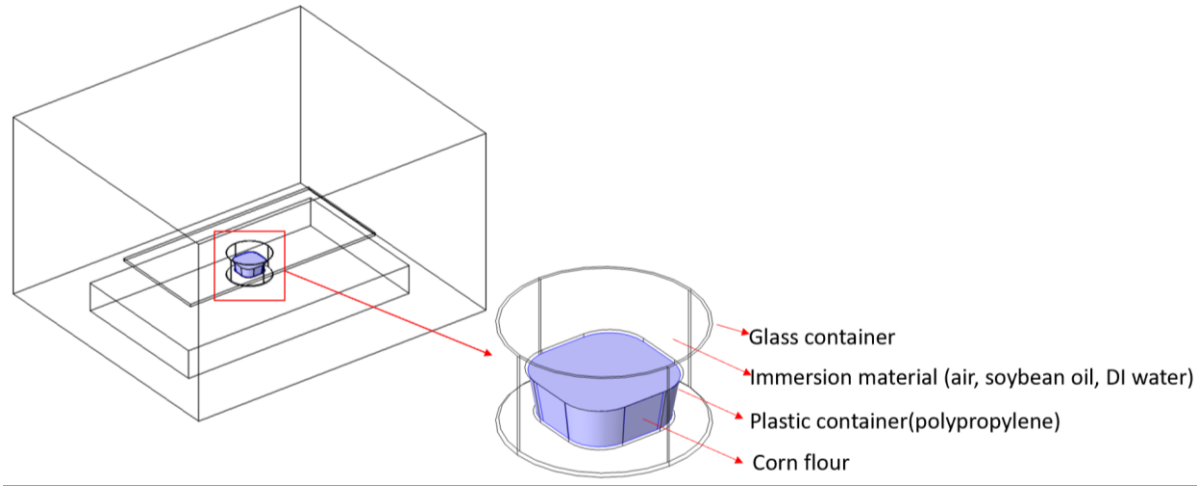
Appendices

Table 2.1. Parameters of the RF simulation.

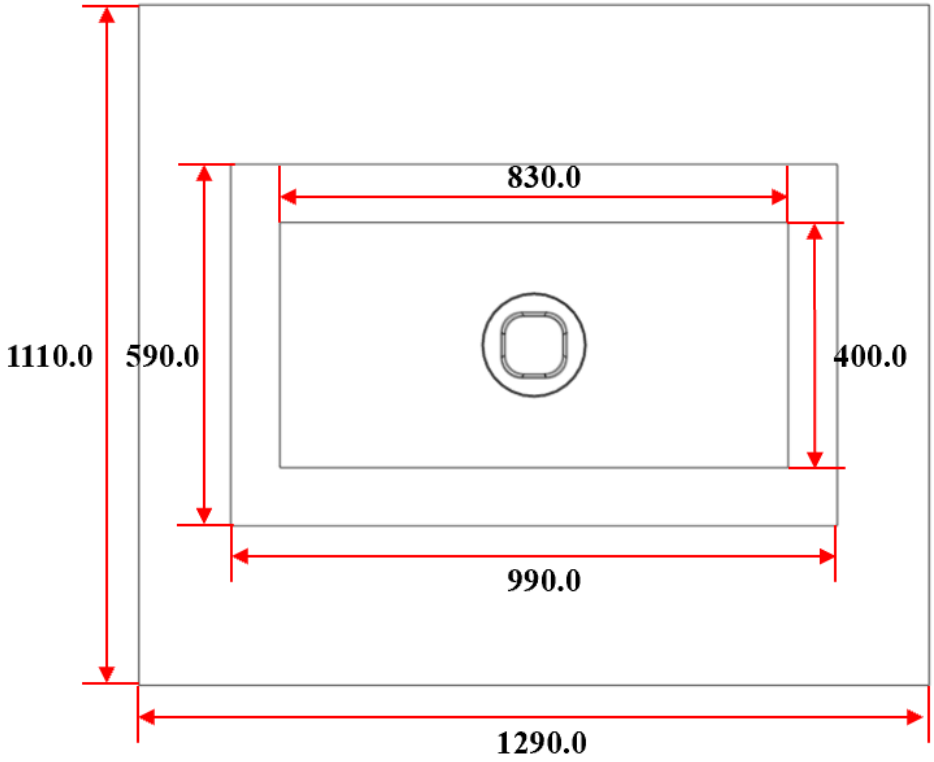
Parameter		Values	Units	Sources
Density				
Corn flour		900	$kg•m^{-3}$	Calculated in this study
Air		Ideal gas law		
DI water		998	$kg•m^{-3}$	Choi Y and Okos, (1986)
Soybean oil		960	$kg•m^{-3}$	Inoue et al., (2002)
Polypropylene		900	$kg•m^{-3}$	Huang et al., (2016)
Glass		2210	$kg•m^{-3}$	Comsol material library
Thermal conductivity				
Corn flour		0.176	$W•m^{-1}•K^{-1}$	Calculated based on Ozturk et al., (2017) and corn flour density
Air		0.026	$W•m^{-1}•K^{-1}$	Comsol material library
DI water		0.58	$W•m^{-1}•K^{-1}$	Abdullah et al., (2016)
Soybean oil		0.153	$W•m^{-1}•K^{-1}$	Arabo, (2011)
Polypropylene		0.26	$W•m^{-1}•K^{-1}$	Huang et al., (2016)
Glass		1.4	$W•m^{-1}•K^{-1}$	Comsol material library
Specific heat capacity				
Corn flour		2.12	$kJ•kg^{-1}•K^{-1}$	Ozturk et al., (2017)
Air		1.005	$kJ•kg^{-1}•K^{-1}$	Comsol material library
DI water		4.178	$kJ•kg^{-1}•K^{-1}$	Choi Y and Okos, (1986)
Soybean oil		1.675	$kJ•kg^{-1}•K^{-1}$	Fasina and Colley, (2008)
Polypropylene		1.8	$kJ•kg^{-1}•K^{-1}$	Huang et al., (2016)
Glass		0.730	$kJ•kg^{-1}•K^{-1}$	Comsol material library
Dielectric properties				
Corn flour	20 °C	6.62 - j•0.30		Calculated based on Ozturk et al., (2017) using mixture equations
	80 °C	18.14 - j•1.86		
Air		1.00 - j•0.00		Comsol material library
Deionized water	20 °C	80.10 - j•0.10		Lau et al., (2020)
	60 °C	66.20 - j•0.50		
Soybean oil		3.00 - j•0.15		Inoue et al., (2002)
Polypropylene		2.00 - j•0.0023		Huang et al., (2016)
Glass		4.20 - j•0.00		Comsol material library

Table 2.2 Summary of the simulated RF heating performance of corn flour immersed in various fluids.

Immersion fluids	Temperature, °C					Uniformity index
	Max	Min	Max - Min	Average temperature	Standard deviation	
Air	67.5	32.5	35.0	48.7	9.1	0.33
Deionized water	43.1	23.1	20.0	34.2	4.5	0.33
Soybean oil	76.4	47.1	29.3	61.4	7.8	0.19

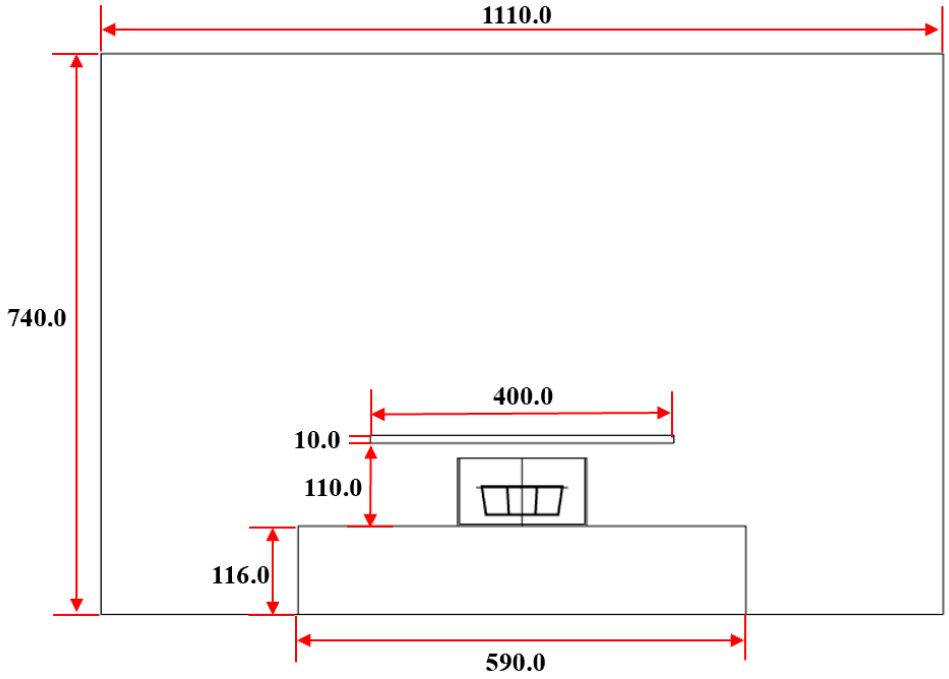


(a)

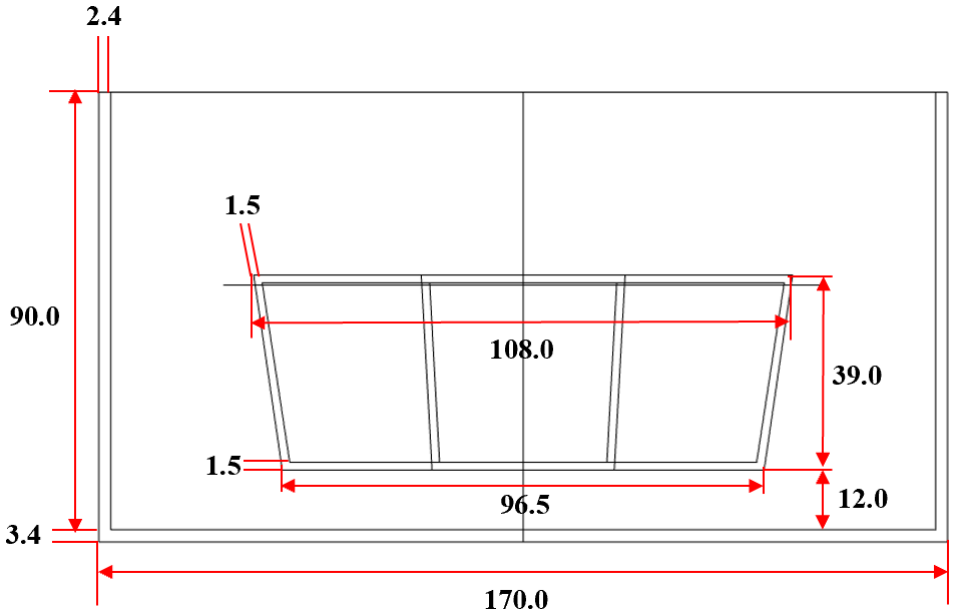


(b)

Figure 2.1. Geometric model of the 6 kW, 27.12 MHz pilot scale free-running oscillator RF system in 3D view (a), top view (b), front view (c), and front view of the product (d). (unit: mm)



(c)



(d)

Figure 2.1. (continued)

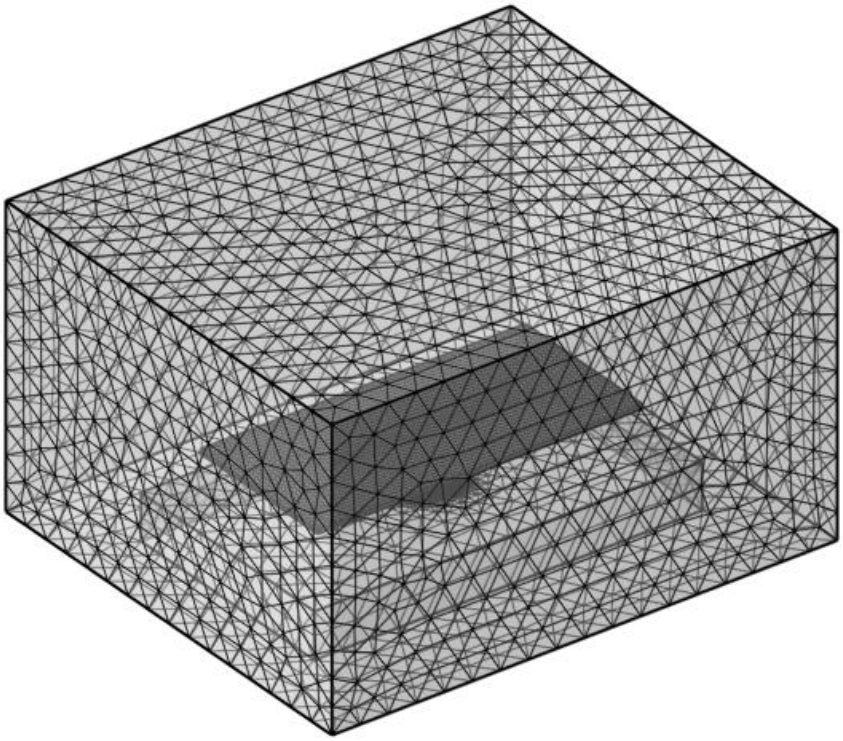


Figure 2.2. Finite-element-method-based meshing for the RF system.

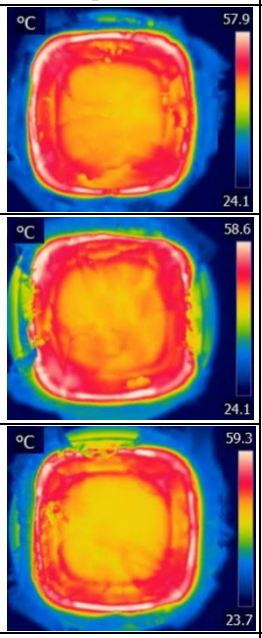
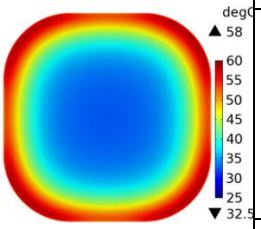
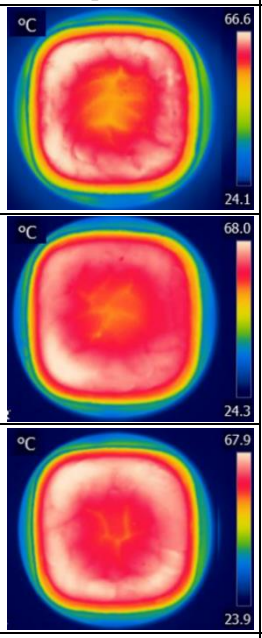
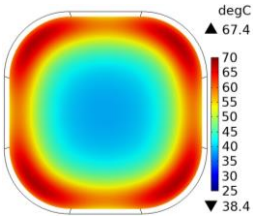
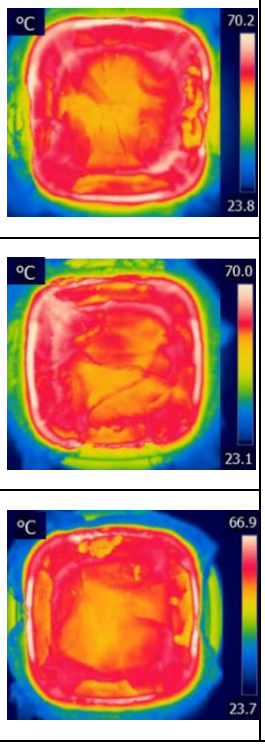
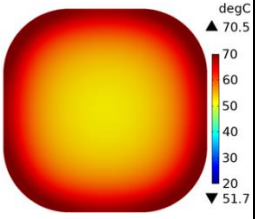
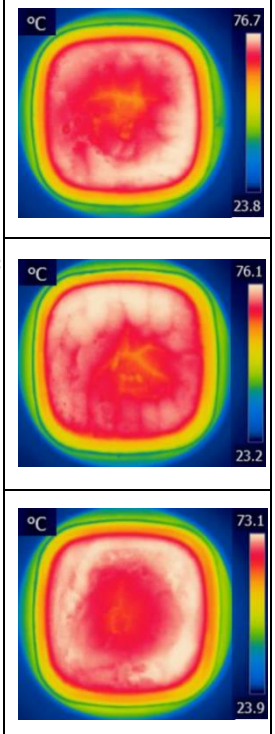
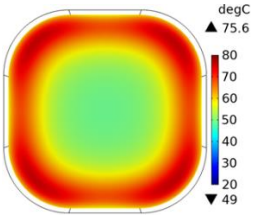
Immersion fluid	Top surface temperature, ºC		Middle slice temperature, ºC	
	Experiment	Simulation	Experiment	Simulation
Air				
Soybean oil				

Figure 2.3. The experimental and simulated temperature profiles at the top surface and middle sliced layers of corn flour after 5 min of RF heating with immersion fluids of air, soybean oil, and deionized water.

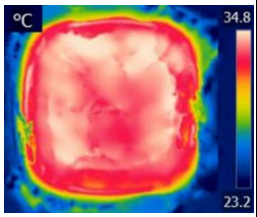
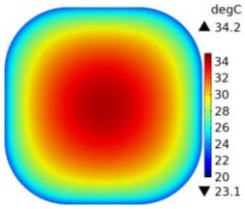
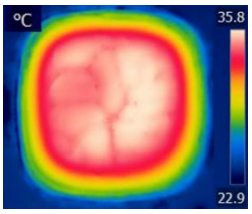
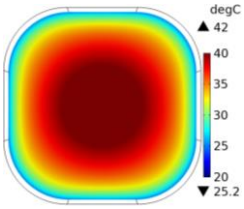
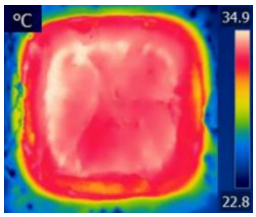
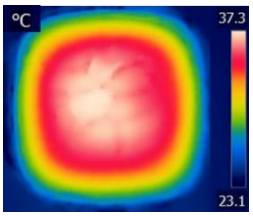
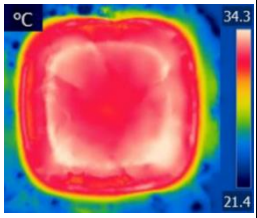
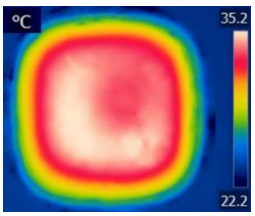
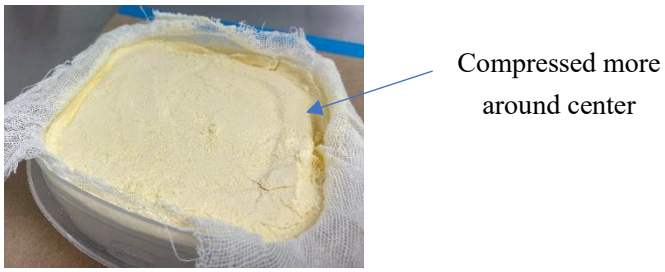
Immersion fluid	Top surface temperature, ºC		Middle slice temperature, ºC	
	Experiment	Simulation	Experiment	Simulation
Deionized Water				
				
				

Figure 2.3. (continued)



(a) Uneven container lid



(b) Unevenly compressed sample

Figure 2.4. The uneven container lid (a) and unevenly compressed corn flour sample (b).

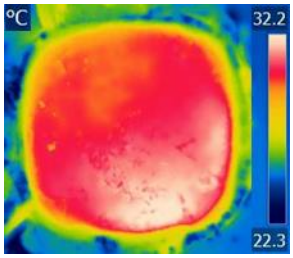
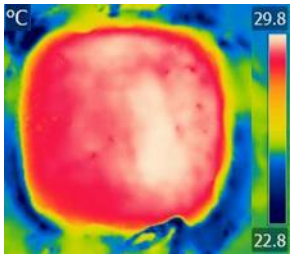
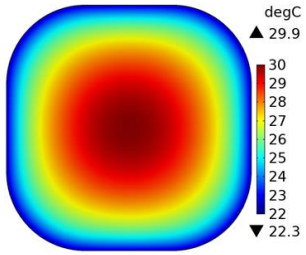
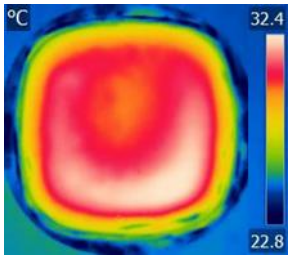
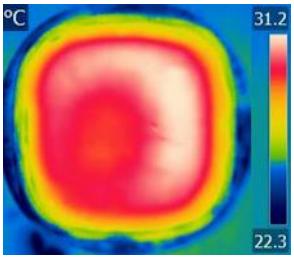
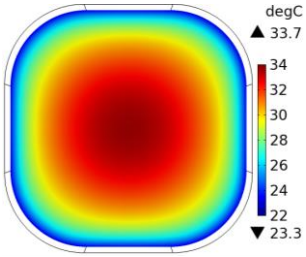
Location	Experiment, °C		Simulation, °C
	Rep 1	Rep 2	
Top			
Middle			

Figure 2.5. The experimental and simulated temperature profiles for 200 g samples immersed in deionized water without severe uneven lid compression.

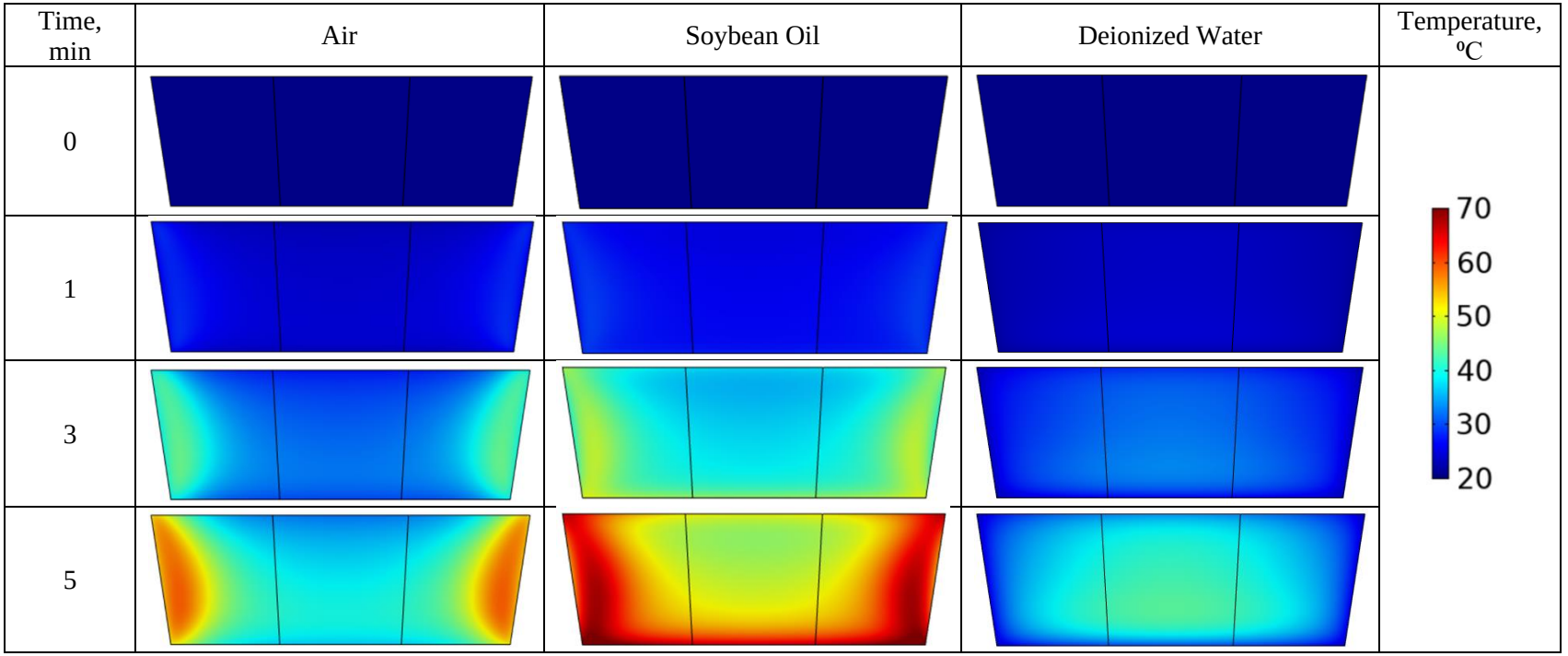


Figure 2.6. The simulated temperature profiles at vertical central slice of the corn flour sample during RF heating.

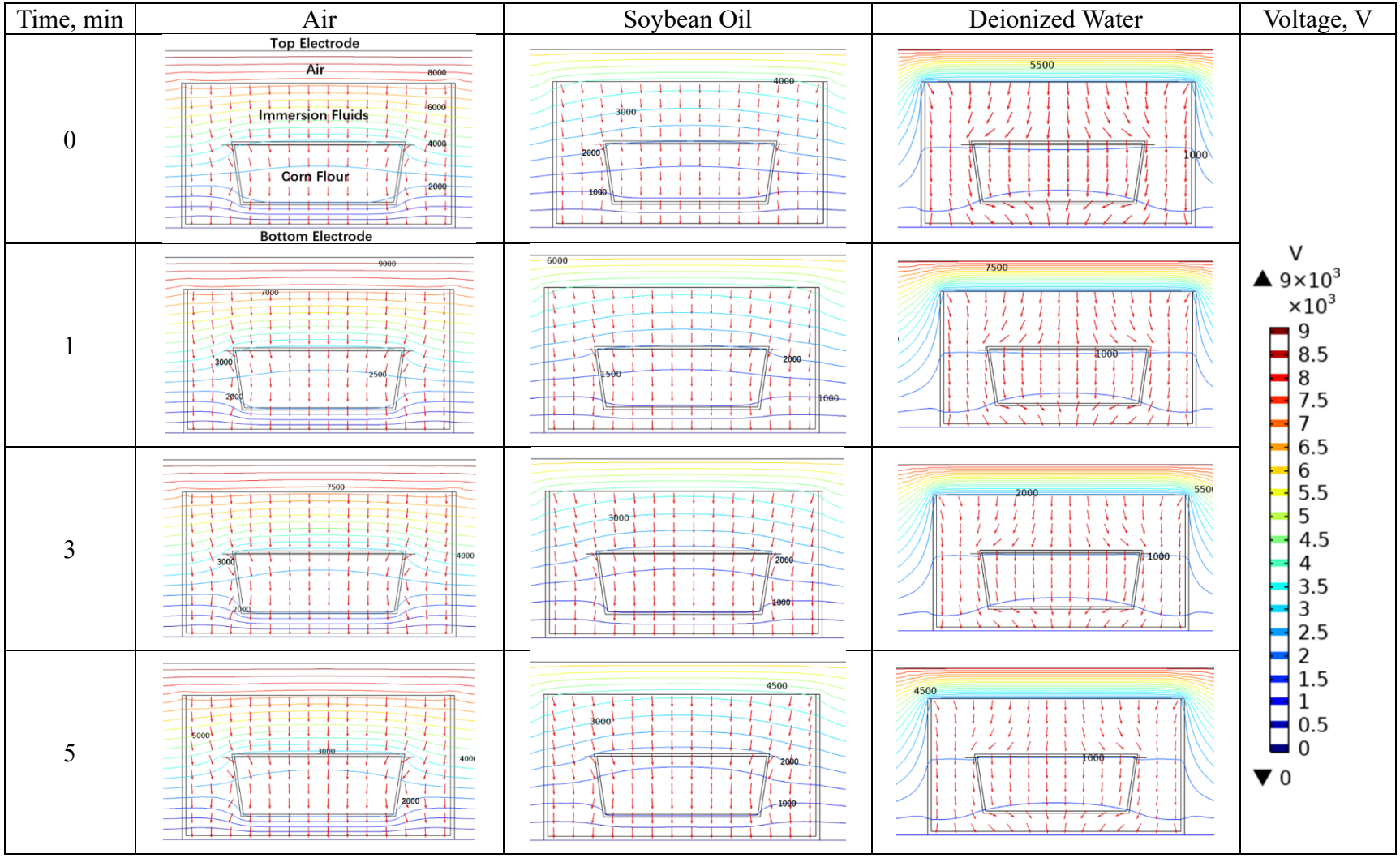


Figure 2.7. Vertical central slice of simulated electric potential gradient contour and electric field distribution within the immersion fluids and corn flour sample at different RF heating time.

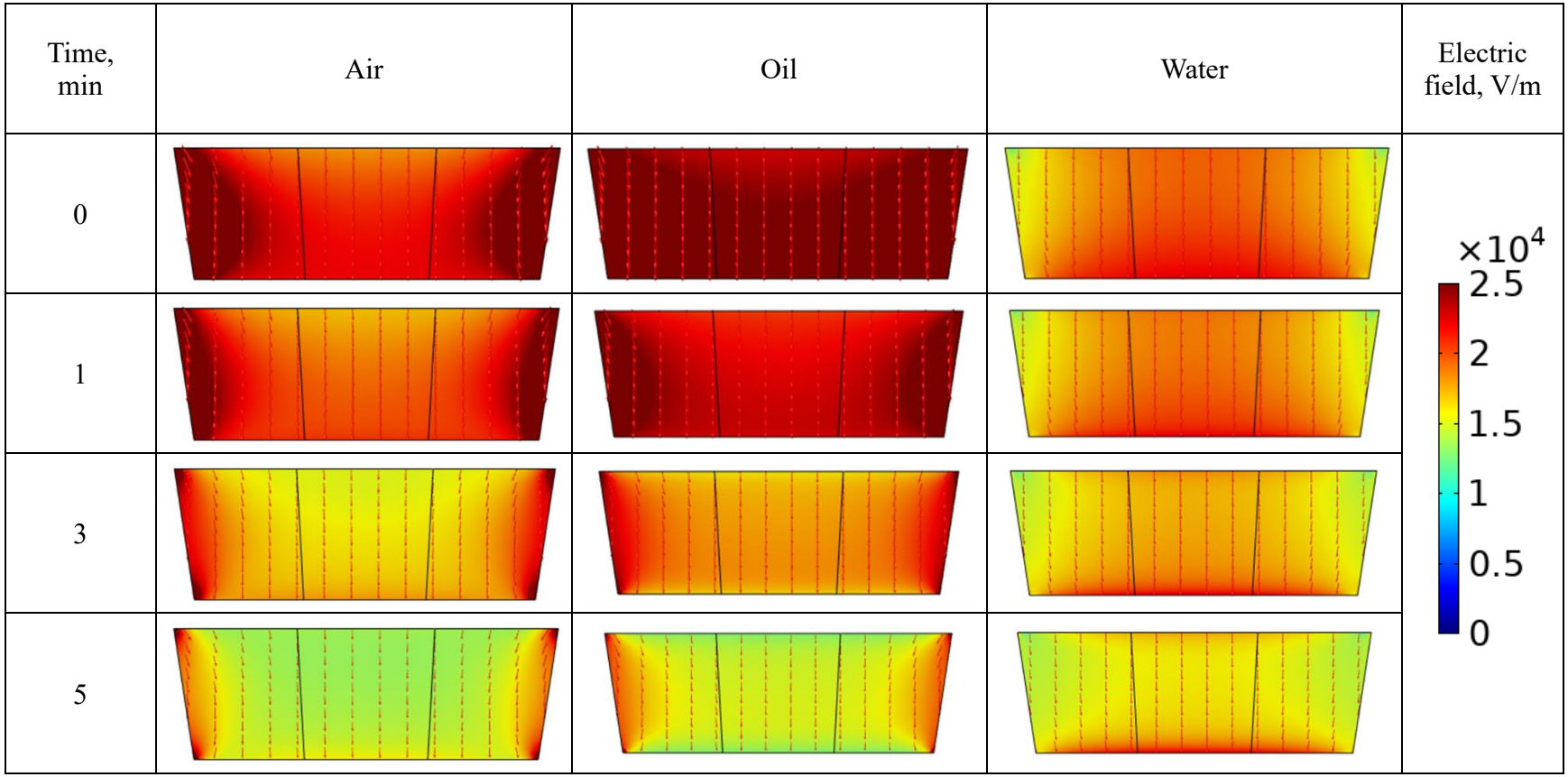


Figure 2.8. Vertical central slice of simulated electric field distribution within the corn flour sample at different RF heating time.

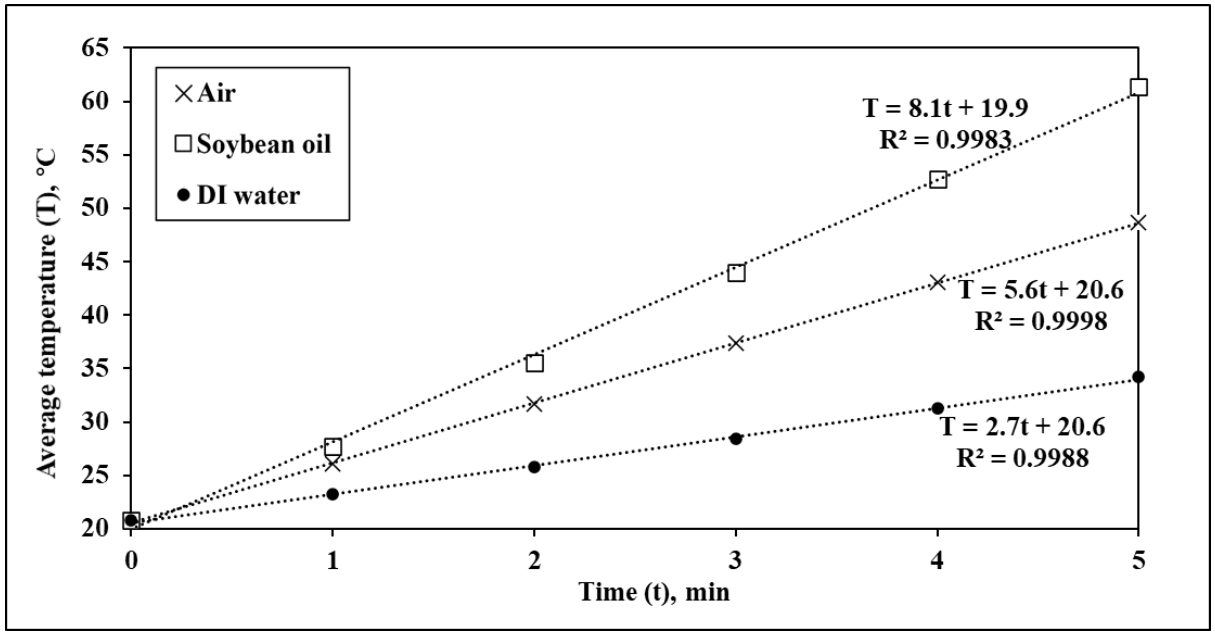


Figure 2.9. Effect of immersion fluids (air, soybean oil, and deionized water) on the simulated average temperature of corn flour.

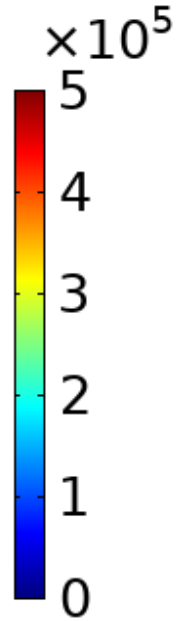
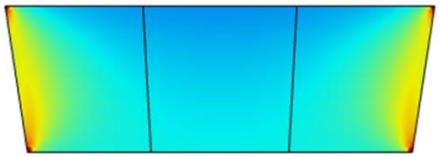
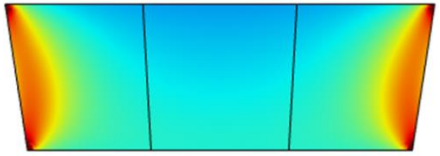
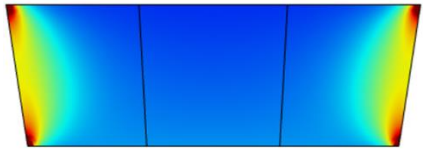
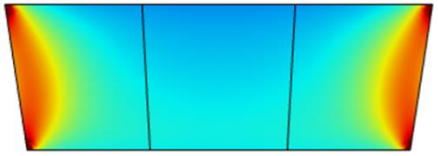
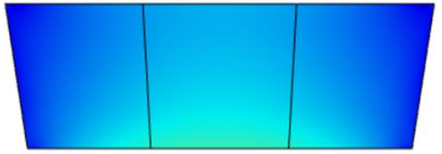
Time, min	Air	Oil	Water	Power absorption, W/m^3
0				
1				
3				
5				

Figure 2.10. Vertical central slice of simulated power dissipation density within the corn flour sample different RF heating time.

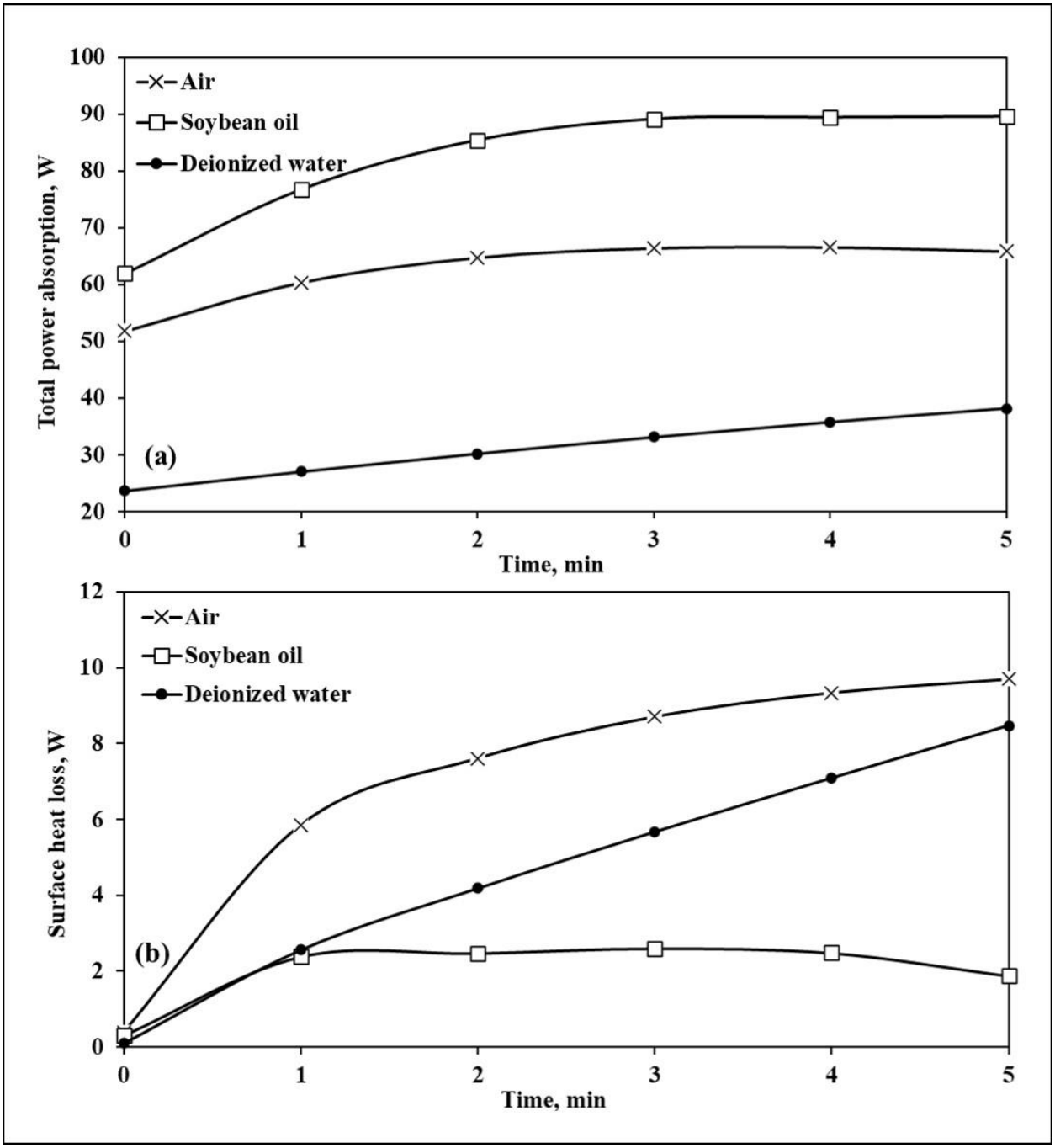


Figure 2.11. Simulated total power absorption (a) and surface heat loss (b) during 5 min of RF heating of corn flour immersed in various fluids.

Chapter 3

Quality Analysis of the All-Purpose Flour Treated with Radiofrequency-Assisted Hot-air Heating Pasteurization

Abstract

Radiofrequency (RF) was a promising technology for pre-heating low moisture food for pasteurization. A previous study showed no significant quality change of the soft wheat flour after RF-assisted hot-air heating. However, the high contents of gluten and damage starch in all-purpose flour may be more sensitive in high-temperature heating. In this study, the bleached and unbleached all-purpose flours were treated by the RF only and RF-assisted hot-air heating at different processing tempeatures (80 °C, 85 °C, and 90 °C). The flour quality and functionality (Sodium dodecyl sulfate sedimentation test, flour swelling power, and solvent retention capacity tests) were investigated and compared to the unprocessed flour. The results show that all the heating conditions significantly changed the overall quality of the bleached and unbleached all-purpose flour, statistically. The higher temperature, longer treatment time, and the bleached flour tended to have more significant changes in the flour quality.

3.1 Introduction

As a low moisture food (typically water activity, $a_w < 0.85$), wheat flour has a strict environment for microorganisms to grow (CAC, 2015). However, when some microbiological contaminations happen during harvesting, processing, or transportation, the pathogenic microbes can stay in the flour product for a long time and may cause severe foodborne problems (Ozturk et al., 2017; Archer et al., 1998). Even though people usually consume the flour product after thermal treatment, the low water activity of flour can increase the heat resistance of pathogenic microbes and increase the chance of inappropriate heating (Archer et al., 1998). Besides, the consumption of raw cookie dough is frequently shown in the United States (Wu et al., 2017). According to a self-reported risky eating behaviors survey among young adults, about 53 % of the participants admitted they had consumed the raw homemade cookie dough (Byrd-Bredbenner et al., 2008). Moreover, the trend of eating raw frozen pizza is also increasing (Wu et al., 2017). These risky eating behaviors highly increase the chance of contracting microbiological contamination and causing foodborne outbreaks in flour, such as *E. coli* and *Salmonella*, which had been reported in the past few years (Eglezos, 2010; U.S. Food & Drug., 2019).

Therefore, finding an efficient method to get rid of the food safety concern from the pathogenic microbial contamination in wheat flour is necessary. However, most of the common physical and chemical processes of flour production, such as milling and bleaching, usually have minimal effect on microbial decontamination (Boreddy et al., 2019; CDC, 2021). To restrain the pathogenic bacterial, thermal treatment is a common and efficient method. However, the conventional thermal treatment usually has low heating efficiency on

pasteurizing low moisture food due to the low thermal conductivity of flours (Saka et al., 2021).

Radiofrequency (RF) heating is a promising technology to heat low moisture foods volumetrically. Unlike the conventional conduction and convection heat transfer, the electromagnetic wave is produced by the high voltage electrode and could penetrate into the food; so the heat can be generated within the food by the molecular frictional interaction (Piyasena et al., 2003) with much higher efficiency than conventional heating.

Many research had proved the feasibility of using RF on pasteurizing the flour-type low moisture products . Kim et al. (2004) compared the effect of RF heating temperature on the particle size of the hard and soft wheat flour and found that hard wheat flours tended to have a higher volume fraction of particles when suspended in water at high temperature. Ozturk et al. (2017) optimized the parameter of RF heating on cornflour and showed faster heating rate and better product quality than the hot air heating. Dag et al. (2021) further improved the RF heating performance by immersed the corn flour sample in the soybean oil. Zhu et al. (2021) used the intermittent RF to dry and measure the physical quality change of native potato flour and the results presented a slightly improved of quality in longer intermittent RF heating because of the tempering effect.

All these studies proved the high efficiency of RF heating, but little research focused on the RF heating influence on the quality and functionality of flour. Boreddy et al. (2019) evaluated the effect of RF-assisted thermal processing with hot air heating on the quality of soft wheat flour. This study reported that, the conditions of air heating at 80 °C for 7 hr and 90 °C for 2 hr after RF preheating to these tempeatures were feasible to pasteurize the soft

wheat flour with no significant compromise in the quality and functionality, especially for the quality that mainly related to the gluten and damage starch (e.g., gluten performance index, Sodium dodecyl sulfate sedimentation, and flour swelling power). Since the main influences of thermal processing on the dough viscosity and rheology are due to the changes in gluten structure and starch configuration (Saka et al., 2021), the thermal processing of RF heating may have more influence on the quality of the hard wheat flour. Usually, the hard wheat flour tends to have more damage starch and higher gluten content than soft wheat flour (Parinyasiri et al., 1991) and the all-purpose flour, which is usually made of hard wheat flour or a combination of soft and hard wheat flour (Kumar et al., 2011). However, the effect of thermal processing, including RF heating, on the quality of hard wheat flour or all-purpose flour has not been evaluated extensively.

All-purpose wheat flour is one of the most popular flours on market due to its composition is suitable for wide range of bakery application. Due to the present of carotenoids, wheat flour usually has an undesirable pale-yellow color in nature after milling (Saiz et al., 2001). To satisfy the consumer requirement, bleaching (also called the chlorine treatment) is a chemical process mainly to improve color acceptability. Besides, the bleaching process also improves the cake baking quality of flour, by increasing the hydrophobicity of starch granules surface and reducing the gluten network forming capacity (Bosmans et al., 2019; Finnie et al., 2006). Thus, the quality response to the thermal processing may be different for bleached and unbleached all-purpose wheat flour as well.

Therefore, the overall objective of this study was to evaluate the effect of RF-assisted pasteurization with hot air oven heating on the quality and functionality of bleached and

unbleached all-purpose flour at various processing conditions (temperature and time).

3.2 Materials & Methods

3.2.1 Materials

Two types of commercially available all-purpose flour were obtained from Costco (Knoxville, TN) and used in this study: the Harvest all-purpose bleached flour (Enriched, Ardent Mills) and the All-Purpose Unbleached Flour (King Arthur). All the chemicals used in this study are lab graded.

3.2.2 Proximate analysis

To characterize the all-purpose wheat flour samples and to determine the composition difference between the bleached flour and unbleached flour samples, the proximate analysis of the samples were determined. The dry basis moisture content was determined by the hot air oven method (AOAC, 2000). The ash content was measured following the AOAC 923.03 method. The water activity was measured by the AquaLab water activity meter (Model 3TE, Decagon devices, USA). The protein content was measured by the combustion method and the crude fat content was measured by the ether extract method. All the measurements were performed for three replications.

3.2.3 Thermal treatment processing and determination of treatment time and temperature

The thermal processing for pasteurization includes two steps: 1) RF heating to heat the sample to the desired temperatures volumetrically; and 2) extend the heating in a hot air oven to achieve pasteurization. In this study, two thermal processing scenarios were performed to

evaluate their effect on the quality of wheat flour. The first processing scenario was to heat the wheat flour to the desired temperature using RF only (referred to as "RF treatment") without achieving pasteurization, and the second processing scenario was to first preheat the sample to the desired temperatures using RF heating following by extended hot air heating for pasteurization (referred to as "RF&A treatment").

Three processing/pasteurization temperatures (80 °C, 85 °C, and 90 °C) were selected as desired temperatures. The RF&A treatment time for each processing temperature was determined based on achieving a 7-log reduction of the *Salmonella* in wheat flour (Boreddy et al., 2019). The D-values of the *Salmonella* in wheat flour (a_w = 0.33) were reported as 25.10 min (80ºC), 13.25 min (85ºC), and 6.22 min (90ºC) (Dodier, 2015). Thus, the extended hot air heating times are 175, 90, and 45 min for 80, 85, and 90, °C, respectively.

A 3 kW, 27.12 MHz pilot-scale free-running oscillator RF heating system (GJG-0.5II-3A-JY, Jiyuan High Frequency, Hebei, China) was used to preheat all the all-purposed flour. Each sample weighed 700 g of unprocessed flour into a rectangle polypropylene container (18.5 cm length, 12.5 cm width, and 4.5 cm height). The flour in the container was evenly shakened to prevent the compression from the cover. The packed samples were placed at the center of the bottom electrode in the RF system. The electrode gap was set as 10 cm, which was preliminarily tested to reach the relative uniform heating. The RF heating was stopped when the cold spot (determined as the point 3 in Figure 3.1.) reached the desired heating temperature. For the RF&A treatment, the RF heated samples were moved to a hot air oven immediately for extended heating.

The RF treated and RF&A treated samples were sealed in Ziploc slider gallon storage

bags, then cooled down to room temepature and stored in the refrigerator at about 4 °C for quality and functionality analysis. All the flours were analyzed within 1 week to prevent the influence from oxidation .

3.2.4 Quality and functionality analysis

3.2.4.1 Color

The color measurement was measured by the colorimeter HunterLab MiniScan XE Plus spectrophotometer (HunterLab Associates, Reston, VA, USA). Before measurement, the colorimeter was calibrated by black and white calibration ceramics. Then add 3 g of flour to ensure the sample covered the cross section of the cylindrical sample plate. The L*, a*, b* values of the sample were recorded. The L* value represents the lightness of the sample, and the range is from 0 (black) to 100 (white). The a* value is related to redness (higher positive is redder and higher negative is greener), and the b* value is related to yellowness (higher positive is more yellow and higher negative is bluer). Both a* and b* values do not have specific numerical limits. All the color data for each treatment groups were compare to the unprocessed flour group and calculate the total color difference, ΔE, to analyze the color change after different treatments, using Equation 1 (Fernandez-Avila et al., 2017):

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad \text{(Eq. 1)}$$

3.2.4.2 Sodium dodecyl sulfate (SDS) sedimentation test

Sodium dodecyl sulfate (SDS) sedimentation test is a quality test for the gluten strength of the flour. In this study, the SDS test followed the procedure in the Guttieri et al. (2004) with slight modification. The 2.5% SDS solution and the 1.1% lactic acid solution were prepared before the experiment. In each replication, 1.0 g of flour was mixed with 10 mL of

water in the 25 mL glass graduated cylinder and shook vigorously for 15 sec. Then the cylinder was rested horizontally on the rocker. After 2 min, the cylinder was inverted four times. Then, 10 mL SDS solution were added into the cylinder. The four-time inversion and 2-min resting of the cylinder were repeated for four times. After these steps, 5 mL of lactic acid solution was added into the cylinder, and the cycle of four-time inversion and 2-min resting were performed for four times also to well mix the sample. At last, the sample was settled vertically for 20 min and the final sediment volume was recorded.

3.2.4.3 Flour Swelling power

The flour swelling power is usually selected as quality analysis of the starch paste viscosity in the noodle. The procedure used in this study followed that in Boreddy et al. (2019), where the procedure was modified from McCormick et al. (1991). Generally, the measurement steps include mixing flour with distilled water, shaking the sample at a 70 °C water bath, heat the sample in the boiling water, and centrifuge to separate supernatant and sediment. The sediment weight was recorded and used to determine the swelling power, which was calculated as the ratio of sediment weight to the sample dry weight.

3.2.4.4 Solvent retention capacity (SRC) tests

The Solvent Retention Capacity (SRC) was to measure the weight percentage of flour sample that perform on four different solvents: 5% lactic acid (LA), 5% sodium carbonate (SC), 50% sucrose, and deionized water. The SRC values were expressed as % of flour weight on 14% moisture content basis. The procedures in this study followed the AACC International Approved Method 56-11 (Steertegem et al., 2013a) with little modification. To ensure the quality of the solution, only 500 g of each solution was prepared each time and

used within 3 days. Also, the sucrose solution should be made 12 hr in advance.

On the other hand, there were some big changes on the equation of the SRC percentage in this study. In the AACC (2000), they used the following equation to calculate the percentage of SRC value:

$$\%\ \mathrm{SRC}\ =\ \left[\left(\frac{gel\ weight}{flour\ weight}\times\frac{86}{100-\%\ flour\ mositure}\right)-1\right]\times 100 \quad \text{(Eq. 2)}$$

However, the weight of solvent retained by the flour can be too large and the moisture correction will have small influence if the calculation followed by this equation.

According to Haynes et al. (2009), they corrected the SRC percentage value equation as: $\%\ \mathrm{SRC}\ =\ \left[\left(\frac{\text{gel weight}}{\text{flour weight}}-1\right)\times\frac{86}{100-\%\ \text{flour mositure}}\right]\times 100$ (Eq. 3)

Therefore, compare to previous equation, the new equation usually gets a higher SRC percentage value.

To better predict the overall performance of flour glutenin with other flour polymers, the gluten performance index (GPI) of each flour conditions were calculated by the following equation (Kweon et al., 2011):

$$GPI\ =\ \frac{5\%\ Lactic\ acid\ SRC}{5\%\ Sodium\ carbonate\ SRC+50\%\ Sucrose\ SRC} \quad \text{(Eq. 3)}$$

3.2.5 Statistical analysis

The RF and RF&A treatment at each condition were carried out in triplicate, and each quality analysis test for each treatment replicate was performed for three replications. Thus, each quality analysis was performed nine times. All the data from each quality test were used to compare among the unprocessed, RF treated, and RF&A treated samples at various temperature & time conditions. . The significance of differences ($P < 0.05$) between different treatment groups were evaluated by the Turkey's test.

3.4 Results & Discussion

3.4.1 Proximate analysis of unprocessed bleached and unbleached flour

The proximate analysis (moisture content in dry basis, water activity, protein content, crude fat content, and ash content) of the commercial bleached and unbleached flour are shown in Table 3.1. From Boreddy et al. (2019), the protein content of the soft wheat flour could reach 10.37 ± 0.17 %, which was smaller than our unprocessed unbleached flour but higher than bleached flour. However, since our moisture content was higher than theirs, the protein content of unprocessed bleached flour was still higher than the soft wheat flour sample after calculation. Besides, they also mentioned their soft wheat flour tended to be a little higher than the other soft wheat flour. Furthermore, the protein contents of our samples were closed to the value from the USDA data base (unbleached flour is 12% and bleached flour is 10.9 %) (USDA, 2020a, 2020b).

3.4.2 Quality and functionality for processed flour

3.4.2.1 Moisture

The average final moisture contents of the unbleached and bleached flour under RF treatment and RF&A treatment are shown in Figure 3.2. As seen in Figure 3.2(a), the moisture content of the unbleached sample decreased significantly after RF treatment for processing tempeatures. The extended hot air heating decreased the moisture content further due to the longer heating time. The higher RF heating temperature also caused slightly higher moisture loss for the unbleached sample. However, the moisture loss of the sample after extended heating at higher tempeature was smaller than that at lower temperature, which was

because the sample was heated for longer time at lower temperature to achieve same pasteurization result. The bleached sample showed a similar moisture loss trend to the unbleached samples.

The decrease of moisture content may influence the efficiency of pasteurization (or pasteurization) since the decreasing water activity could increase the thermal resistance of pathogenic microbes (VanCauwenberge et al., 1981).

3.4.2.2 Color

The color measurement (L*, a*, and b*) of the unbleached and bleached flour under different condition were shown in the Table 3.2. The lightness color (L* value) of the unbleached (85.22 ± 0.58 to 86.90 ± 0.26) and bleached flour (86.59 ± 0.37 to 87.12 ± 0.32) after different thermal processed conditions were generally not significant different from that of the unprocessed unbleached (86.53 ± 0.27) and bleached (87.94 ± 0.5). However, the thermal processing at some conditions caused significant changes on the a* and b*values. Both the unbleached and bleached flour after thermal treatment had the a* value at the range of 0.22 ± 0.04 to 0.36 ± 0.04, and it was significantly different compare to those unprocessed unbleached (0.46 ± 0.05) and bleached (0.37 ± 0.04) flour. Nevertheless, since all the a* values were small and close to 0, the color change in visual were not that significantly. Similar results were reported in the RF and hot air heating of soft wheat flour (Boreddy et al., 2019). The b* value after thermal processed also significantly changed when compared to the unprocessed flour. For the unbleached flour, the unprocessed value was 9.50 ± 0.25 and changed to 9.38 ± 0.34 to 10.35 ± 0.32 after thermal treatment; and the unprocessed bleached flour was 9.77 ± 0.38 and changed to 8.38 ± 0.11 to 9.90 ± 0.35 after thermal treatment.

To better understand the overall color change after treatment, the Figure 3.3 shows the total color difference (ΔE) after different treatments. For the unbleached flour, the ΔE generally increased with the temperature and the extended heating time. However, for the bleached flour, the ΔE did not show significant difference among different treatments. The different trends between unbleached and bleached samples might be attributed to the benzoyl peroxide, the bleaching agent that oxidize the carotenoids in flour (Saiz et al., 2001).

Nevertheless, for all the samples with different treatments, the ΔE values were smaller than 2, indicating little color change (Cruse, 2014). Therefore, although the higher temperature and longer heating time may change the color of the wheat flour, the color change is minimal during the RF and extended hot air heating process.

3.4.2.3 Sodium dodecyl sulfate (SDS) sedimentation test

The SDS sediment values at different thermal processing conditions are shown in Figure 3.4, which measures the relative gluten strength in the wheat flour. The SDS results of unprocessed unbleached flour in this study was much higher than the results in Guttieri et al. (2004) (sample used the crossing genotype flour for making cookie) and lower than the results of hard wheat flour (Slaughter et al., 1992), and matched with the SDS value range of 18 Argentine wheat cultivars in Colombo et al. (2008). The higher SDS value is related to stronger gluten and better bread baking quality (DICK et al., 1983). The high temperature of RF treatment can cause a low SDS value since it tends to have a more negative influence on the gluten quality. As explained in Schofield et al. (1983), the high temperature treatment which was above 55°C would cause the loss of gluten functionality (baking performance). On the other hand, since the bleaching treatment already have negative effect on the gluten

network forming (Bosmans et al., 2019), the bleached flour may get less negative influence from heat treatment when compare to the unbleached. That may be the reason why the bleached flour had less significantly decrease on the SDS value as the treatment had higher temperature. Furthermore, different cultivar has different quality, which is differentiated their SDS value (Carter et al., 1999). Even the protein concentration related to the SDS value positively, but there are some cultivars can be less change on the SDS as the protein concentration change.

Back to the trend of SDS value change under different thermal condition, the SDS values of the the unbleached wheat flour decreased significantly with the increasing RF temperature and the extended hot air heating time, as shown in Figure 3.4 (a). However, the SDS values of the unbleached flour after RF heating were in the acceptable range from Colombo et al. (2008) (11.75 ml to 19.25 ml), which the values were between the soft and hard wheat flour, and close to values of the all-purpose flour. For the bleached wheat flour, the SDS values did not significantly change after RF heating at 80 and 85 °C, while significantly decreased after extended hot air heating at these tempeatures. Both the RF heating and RF&A heating at 90 °C significantly decreased the SDS values when compared to the unprocessed bleached wheat flour. The results were different from the SDS values of the soft wheat flour reported in Boreddy et al. (2019), where the SDS did not signficantly change at different processing conditions. The significant change of SDS in this study might be attributed to the higher gluten content in the all-purpose flours (Parinyasiri et al., 1991; Kumar et al., 2011).

3.4.2.4 Flour Swelling power

Swelling power is related to the paste viscosity degree of heated starch suspension, and it is usually used as a test for the eating quality of noodle (McCormick et al., 1991). Figure 3.5 showed the flour swelling power of both unbleached and bleached flour under different thermal processing conditions. Generally, the flour swelling power increased with the RF heating temperature and the extended heating for both unbleached and bleached samples. The extended hot air heating was critical in increasing the flour swelling power significantly. Boreddy et al. (2019) also reported that the swelling power in soft wheat flour can be significantly increased by the RF&A heating processes. The significant increase may be because the heat treatment can change the amylose to a more amorphous form, and the amylose can combine with more water to increase the swelling power (Senanayake et al., 2013). A similar trend also happened in Oh et al. (2018), which sample was high amylose rice starch and the heat treatment temperature was higher than our study. Their research showed that the paste viscosity increased with increased temperature but decreased with longer processing time. Moreover, the significant increase of flour swelling power is a positive trending for the noodle quality (McCormick et al., 1991).

3.4.2.5 Solvent retention capacity (SRC) tests

The SRC test is commonly used in the commercial bakery quality test, which measures the functionality and performance of flour and quantifies the flour retention in different solvents after centrifugation: 5% lactic acid, 5% sodium carbonate, 50% sucrose, and water (Guttieri et al., 2004). The four SRC values of unbleached and bleached all-purpose flour after different RF and hot air heating treatments were shown in the Figure 3.6 and 3.7,

respectively. The SRC value of the unprocessed flours matched well with the results from previous research. Xiao et al. (2006) showed the wide SRC value range of hundreds of hard wheat flour samples, and the results in this study were within the range or even greater than the mean value. On the other hand, both the unprocessed bleached and unbleached had greater SRC values than the Boreddy et al. (2019). These trend means the flour in this study was more suitable for bread making. Also, the SRC values of the unprocessed unbleached flour in this study were generally close to the multipurposed flour (Ee et al., 2020).

The lactic acid SRC (LA-SRC) is a value to measure the flour gluten strength and correlated to the SDS test. Both the LA-SRC and SDS tests use the lactic acid solution and are related to the protein quality in the flour (Xiao et al., 2006). For unbleached wheat flour, the RF treatment at lower temperatures (80 and 85 °C) did not change the LA-SRC value significantly; while all other processing conditions significantly decreased the LA-SRC value, as shown in Figure 3.6 (a). This may be because the long-time treatment with high temperature can decrease the swelling ability of the gluten network which is desired for the cookie or cake making (Steertegem et al., 2013b). However, the LA-SRC of bleached flour significantly decreased after all various RF and RF&A treatments with different tempeatures.

The sodium carbonate SRC (SC-SRC) is positively related to the starch damage caused by the milling process, since sodium carbonate can ionize the starch polymers end to increase its water-binding capacity. Hard wheat flour tends to have more starch damage, which causes a higher SC SRC value (Parinyasiri et al., 1991). In this study, all the thermal treatments (both unbleached and bleached) had not significantly change when compared to the unprocessed flours, except the RF treatment at 85 °C and RFA treatment at 80°C and 85 °C.

The sucrose SRC (S-SRC) is the value related to the arabinoxylans (or pentosans) content in the sample, and it highly affected the water absorption of baked products. Higher arabinoxylans content means higher water absorption of the sample, which is beneficial to the bread products but undesirable to the cookie or cracker products (Baker Pedia, n.d.; USDA, 2017). For the unbleached flour, the S-SRC values did not show significant difference among different RF and RF&A treatments, except the RF&A treatment at 90 °C.

The water SRC (W-SRC) value is the best quality predictor of the baked product, and it represents the sample water holding capacity to different macro-polymers (glutenin, damaged starch, pentosans). The lower W-SRC value is better for the baked product which is usually made with soft wheat flour (cookies, cakes, and crackers, etc.). On the other hand, however, the lower W-SRC is worse for bread making (usually made by the hard wheat flour or all-purposed flour) (Baker Pedia, n.d.). The W-SRC values of both the bleached and unbleached flours increased as temperature went higher. The W-SRC values of the unbleached samples had less significant change after RF treatment, but the values significantly increased after extended hot air heating after pasteurization, as shown in Figure 3.6. (a). Therefore, flour increases the overall water retention capacity as more severe change on the thermal treatment (Steertegem et al., 2013b). Similar results were also observed for the bleached wheat flour, as shown in Figure 3.7. (a).

Steertegem et al. (2013) investigated the effect of heat treatment on the SRC test of the unbleached flour. It found that both the W-SRC and S-SRC values of wheat flour increased with increased heating time and temeprature, while the LA-SRC decreased as the time and temperature went up; and the SC-SRC value had variations without clear trend. These

findings generally match with the resutls in this study.

SRC values have been used in determing the application of flours. For example, Kweon et al. (2011) showed the golden standard SRC value of the cookie and cracker flour (softer wheat), and sponge and dough flour (harder wheat). The standard values of W-SRC, LA-SRC, SC-SRC, S-SRC for cookie and cracker flour are $\leqslant 51$, $\geqslant 87$, $\leqslant 64$, $\leqslant 89$, respectively; while the standard values of W-SRC, LA-SRC, SC-SRC, S-SRC for sponge and dough flour are $\leqslant 57$, $\geqslant 100$, $\leqslant 72$, $\leqslant 96$, respectively. However, the blended (soft and hard) wheat flour could have a wider range of SRC values as reported by Kweon et al. (2011). The ranges of W-SRC, LA-SRC, SC-SRC, and S-SRC are 52.2% to 89.4%, 71.2% to 161.8%, 69.1% to 128.0%, 76.6% to 145%, respectively. In this study, even though the samples after pasteurization were significantly changed in the statistical point of view, the absolute change of these average values are minimum (ranged between 0.23% and 8.70 %), and all the SRC values were in the range of blended wheat flour and not the extreme value, indicating that the influences of both the RF and RF&A on the all-purpose flour were still in the practical range and will not influence the application of wheat flours.

The gluten performance index (GPI) is an overall index that is calculated using eq. 3, which represented overall performance of flour glutenin in the environment of other modulating networks of flour polymers (Kweon et al., 2011). The GPI index of unbleached and bleached flour after different thermal treatments were shown in Figure 3.8. The GPI values of the unbleached flour did not significantly change after RF heating (except RF 90°C); but decreased significantly after RF&A treatment, indicating the influence of the extended heating. For the bleached flours, the GPI values significantly decreased after all RF

and RF&A treatments. Boreddy et al. (2019) evaluated the RF&A treatment on the GPI values of soft wheat flour and found no significant difference between the unprocessed and processed flous.

The GPI index shown in Boreddy et al. (2019) were slightly higher than the results in this study. As previous results mentioned that the sucrose SRC value in this study may be too high, which was to lower the GPI value. Nevertheless, a previous study also had a lower GPI results of multipurposed flour (average value was 0.55) compare to this study results (Ee et al., 2020), and all the GPI results (include both unprocessed and processed all-purpose flours) in our study were lower than the average GPI value of bread flour value (0.66) and higher than the average GPI value of cake flour (0.46). Besides, the new equation from (Kweon et al., 2011) will slightly increase all the SRC and cause a slightly lower value in GPI. In this study, even though the GPI values of the flour after all the RF treatments were significantly changed statistially, the changes were still acceptable for the practical range.

3.5 Conclusion

The moisture content of both unbleached and bleached flours after RF treatments significantly decreased as the temperature went up; while the moisture content of flour after the RF&A treatment was also significantly lower than the unprocessed flour, but the moisture loss were less at higher processing tempeatures due to the much shorter heating time. All the color changes were not visually different. The SDS value of unbleached flour was significantly decreased after all the heating treatments. At the same temperature treatment, the SDS value of the RF&A treatment was lower than that of the RF treatment; similar trend happened in

bleached flour. All the flour swelling powers increased with the processing temperature, and the value of RF&A was always significantly higher than the RF treatment; but the trending was good for noodle making. For the SRC values, all the LA-SRC values decreased as the processing temperature increased, while the the W-SRC values tended to increase as the processed temperature increase, and the SC-SRC and S-SRC values did not significantly change. Lastly, all the GPI values after thermal treatments (except the RF treatment of unbleached flour) were significantly different from that of the unprocessed flours. Even though most of the SRC and GPI values after RF and RF&A treatment were signifantly changed, the absolute changes were minimum and still in the practical range.

Overall, the RF-assisted hot air heating significantly changed the quality and functionality of the unbleached and bleached all-purpose flours, but most of the changes were in the practical application range or developed to the positive trending More influence was observed for the flour after the RF&A treatment than the RF treatment. The bleached flour showed less significant change than the unbleached flour due to the change that already happened in the property of flour during bleaching.

References

AACC, 2000. Approved Methods of the AACC, in: American Association of Cereal Chemists.

Abdullah, A., Mohamad, I.S., Hashim, A.Y.B., Abdullah, N., Wei, P.B., Isa, M.H., Abidin, S.Z., 2016. Thermal conductivity and viscosity of deionised water and ethylene glycol-based nanofluids. J. Mech. Eng. Sci. ISSN 10, 2249–2261. https://doi.org/10.15282/jmes.10.3.2016.4.0210

AOAC, 2000. AOAC Official Methods 925.10 Solids (Total) and Moisture in Flour. AOAC Off. Methods Anal. 3390.

Arabo, E.Y.M., 2011. Shear and extensional viscosities of hard wheat flour dough using a capillary rheometer. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2010.10.027

Archer, J., Jervis, E.T., Bird, J., Gaze, J.E., 1998. Heat resistance of Salmonella weltevreden in low-moisture environments. J. Food Prot. https://doi.org/10.4315/0362-028X-61.8.969

Baker Pedia, n.d. Solvent Retention Capacity (SRC) | Baking Processes | BAKERpedia [WWW Document]. URL https://bakerpedia.com/processes/solvent-retention-capacity/ (accessed 7.12.21).

Birla, S.L., Wang, S., Tang, J., 2008. Computer simulation of radio frequency heating of model fruit immersed in water. J. Food Eng. 84, 270–280. https://doi.org/10.1016/j.jfoodeng.2007.05.020

Boreddy, S.R., Birla, S., Froning, G., Thippareddi, H., Subbiah, J., 2014. Effect of Radio Frequency Assisted Thermal Processing on Quality and Functional Properties of Egg

White Powder. Trans. ASABE 57, 1761–1770. https://doi.org/10.13031/trans.57.10781

Boreddy, S.R., Rose, D.J., Subbiah, J., 2019. Radiofrequency-Assisted Thermal Processing of Soft Wheat Flour. J. Food Sci. 84, 2528–2536. https://doi.org/10.1111/1750-3841.14767

Bosmans, G.M., Peene, L.J., Van Haesendonck, I., Brijs, K., Delcour, J.A., 2019. Impact of chlorine treatment on properties of wheat flour and its components in the presence of sucrose. Food Chem. 274, 434–443. https://doi.org/10.1016/j.foodchem.2018.09.019

Byrd-Bredbenner, C., Abbot, J.M., Wheatley, V., Schaffner, D., Bruhn, C., Blalock, L., 2008. Risky Eating Behaviors of Young Adults-Implications for Food Safety Education. J. Am. Diet. Assoc. https://doi.org/10.1016/j.jada.2007.12.013

CAC (Codex Alimentarius Commision), 2015. CODE OF HYGIENIC PRACTICE FOR LOW-MOISTURE FOODS.

Carter, B.P., Morris, C.F., Anderson, J.A., 1999. Optimizing the SDS sedimentation test for end-use quality selection in a soft white and club wheat breeding program. Cereal Chem. 76, 907–911. https://doi.org/10.1094/CCHEM.1999.76.6.907

CDC, 2021. Say No to Raw Dough [WWW Document]. URL https://www.cdc.gov/foodsafety/communication/no-raw-dough.html (accessed 6.10.21).

CDC, 2018. Multistate Outbreak of Salmonella Typhimurium Infections Linked to Dried Coconut | March 2018 | Salmonella | CDC [WWW Document]. URL https://www.cdc.gov/salmonella/typhimurium-03-18/index.html (accessed 1.30.21).

CDC, 2012. Salmonella Bredeney Infections Linked to Peanut Butter [WWW Document]. URL https://www.cdc.gov/salmonella/bredeney-09-12/index.html (accessed 1.30.21).

Chandrasekaran, S., Ramanathan, S., Basak, T., 2013. Microwave food processing - a review.

Food Res. Int. 52, 243–261. https://doi.org/10.1016/j.foodres.2013.02.033

Chen, J., Lau, S.K., Boreddy, S.R., Subbiah, J., 2019. Modeling of radio frequency heating of egg white powder continuously moving on a conveyor belt. J. Food Eng. 262, 109–120. https://doi.org/10.1016/J.JFOODENG.2019.05.029

Chen, J., Lau, S.K., Chen, L., Wang, S., Subbiah, J., 2017. Modeling radio frequency heating of food moving on a conveyor belt. Food Bioprod. Process. 102, 307–319. https://doi.org/10.1016/j.fbp.2017.01.009

Chen, L., Wang, K., Li, W., Wang, S., 2015. A strategy to simulate radio frequency heating under mixing conditions. Comput. Electron. Agric. 118, 100–110. https://doi.org/10.1016/j.compag.2015.08.025

Choi, C.T.M., Konrad, A., 1991. Finite element modeling of the rf heating process. IEEE Trans. Magn. https://doi.org/10.1109/20.105034

Choi Y, Okos, M.R., 1986. Physical and chemical properties of food. ASAE Publ.

Colombo, A., Pérez, G.T., Ribotta, P.D., León, A.E., 2008. A comparative study of physicochemical tests for quality prediction of Argentine wheat flours used as corrector flours and for cookie production. J. Cereal Sci. 48, 775–780. https://doi.org/10.1016/j.jcs.2008.05.003

Cruse, P., 2014. Introduction to Colour Models ('Spaces') [WWW Document]. Berkhamsted, United Kingdom Graph. Qual. Consult. . URL http://www.colourphil.co.uk/lab_lch_colour_space.shtml (accessed 6.13.21).

Dag, D., Singh, R.K., Kong, F., 2021. Effect of immersion medium on radio frequency (RF) heating uniformity of corn flour. J. Food Eng. under Revis.

Dag, D., Singh, R.K., Kong, F., 2019. Dielectric properties, effect of geometry, and quality changes of whole, nonfat milk powder and their mixtures associated with radio frequency heating. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2019.04.017

Datta, A.K., 2001. Handbook of Microwave Technology for Food Application, Handbook of Microwave Technology for Food Application. https://doi.org/10.1201/9781482270778

DICK, J., JW, D., JS, Q., 1983. A MODIFIED SCREENING TEST FOR RAPID ESTIMATION OF GLUTEN STRENGTH IN EARLY-GENERATION DURUM WHEAT BREEDING LINES. A Modif. Screen. TEST RAPID Estim. GLUTEN STRENGTH EARLY-GENERATION DURUM WHEAT Breed. LINES.

Dodier, D., 2015. Comparative Study Of The D-values of Salmonella spp. and Enterococcus faecium in Wheat Flour.

Ee, K.Y., Eng, M.K., Lee, M.L., 2020. Physicochemical, thermal and rheological properties of commercial wheat flours and corresponding starches. Food Sci. Technol. 40, 51–59. https://doi.org/10.1590/fst.39718

Eglezos, S., 2010. Microbiological quality of wheat grain and flour from two mills in Queensland, Australia. J. Food Prot. 73, 1533–1536. https://doi.org/10.4315/0362-028X-73.8.1533

Fasina, O.O., Colley, Z., 2008. Viscosity and specific heat of vegetable oils as a function of temperature: 35°C to 180°C. Int. J. Food Prop. https://doi.org/10.1080/10942910701586273

Fernandez-Avila, C., Gutierrez-Merida, C., Trujillo, A.J., 2017. Physicochemical and sensory characteristics of a UHT milk-based product enriched with conjugated linoleic acid

emulsified by Ultra-High Pressure Homogenization. Innov. Food Sci. Emerg. Technol. 39, 275–283. https://doi.org/10.1016/j.ifset.2017.01.001

Finn, S., Condell, O., McClure, P., Amézquita, A., Fanning, S., 2013. Mechanisms of survival, responses, and sources of salmonella in low-moisture environments. Front. Microbiol. 4. https://doi.org/10.3389/fmicb.2013.00331

Finnie, S.M., Bettge, A.D., Morris, C.F., 2006. Influence of flour chlorination and ingredient formulation on the quality attributes of pancakes. Cereal Chem. 83, 684–691. https://doi.org/10.1094/CC-83-0684

Gao, M., Tang, J., Villa-Rojas, R., Wang, Y., Wang, S., 2011. Pasteurization process development for controlling Salmonella in in-shell almonds using radio frequency energy. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2010.12.021

Gao, M., Tang, J., Wang, Y., Powers, J., Wang, S., 2010. Almond quality as influenced by radio frequency heat treatments for disinfestation. Postharvest Biol. Technol. 58, 225–231. https://doi.org/10.1016/j.postharvbio.2010.06.005

Guttieri, M.J., Becker, C., Souza, E.J., 2004. Application of Wheat Meal Solvent Retention Capacity Tests Within Soft Wheat Breeding Populations. Cereal Chem. 81, 261–266. https://doi.org/10.1094/CCHEM.2004.81.2.261

Haynes, L.C., Bettge, A.D., Slade, L., 2009. Soft wheat and flour products methods review: Solvent retention capacity equation correction. Cereal Foods World. https://doi.org/10.1094/CFW-54-4-0174

Hu, S., Zhao, Y., Hayouka, Z., Wang, D., Jiao, S., 2018. Inactivation kinetics for Salmonella typhimurium in red pepper powders treated by radio frequency heating. Food Control.

https://doi.org/10.1016/j.foodcont.2017.10.034

Huang, Z., Marra, F., Subbiah, J., Wang, S., 2018a. Critical Reviews in Food Science and Nutrition Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review. https://doi.org/10.1080/10408398.2016.1253000

Huang, Z., Marra, F., Subbiah, J., Wang, S., 2018b. Computer simulation for improving radio frequency (RF) heating uniformity of food products: A review. Crit. Rev. Food Sci. Nutr. https://doi.org/10.1080/10408398.2016.1253000

Huang, Z., Zhang, B., Marra, F., Wang, S., 2016. Computational modelling of the impact of polystyrene containers on radio frequency heating uniformity improvement for dried soybeans. Innov. Food Sci. Emerg. Technol. https://doi.org/10.1016/j.ifset.2015.11.022

Huang, Z., Zhu, H., Yan, R., Wang, S., 2015. Simulation and prediction of radio frequency heating in dry soybeans. Biosyst. Eng. 129, 34–47. https://doi.org/10.1016/j.biosystemseng.2014.09.014

Inoue, C., Hagura, Y., Ishikawa, M., Suzuki, K., 2002. The dielectric property of soybean oil in deep-fat frying and the effect of frequency. J. Food Sci. https://doi.org/10.1111/j.1365-2621.2002.tb09464.x

James, L., Dale, S., 2011. Adhesives Technology for Electronic Applications, Adhesives Technology for Electronic Applications. Elsevier Inc. https://doi.org/10.1016/C2009-0-64364-6

Jiang, H., Gu, Y., Gou, M., Xia, T., Wang, S., 2020. Radio frequency pasteurization and

disinfestation techniques applied on low-moisture foods. Crit. Rev. Food Sci. Nutr. https://doi.org/10.1080/10408398.2019.1573415

Jiao, Y., Shi, H., Tang, J., Li, F., Wang, S., 2015. Improvement of radio frequency (RF) heating uniformity on low moisture foods with Polyetherimide (PEI) blocks. Food Res. Int. https://doi.org/10.1016/j.foodres.2015.04.016

Jiao, Y., Tang, J., Wang, S., 2014. A new strategy to improve heating uniformity of low moisture foods in radio frequency treatment for pathogen control. J. Food Eng. 141, 128–138. https://doi.org/10.1016/j.jfoodeng.2014.05.022

Kim, W., Choi, S.G., Kerr, W.L., Johnson, J.W., Gaines, C.S., 2004. Effect of heating temperature on particle size distribution in hard and soft wheat flour. J. Cereal Sci. 40, 9–16. https://doi.org/10.1016/j.jcs.2004.04.005

Kumar, P., Yadava, R.K., Gollen, B., Kumar, S., Kant Verma, R., Yadav, S., 2011. Nutritional Contents and Medicinal Properties of Wheat: A Review, Life Sciences and Medicine Research.

Kweon, M., Slade, L., Levine, H., 2011. Solvent retention capacity (SRC) testing of wheat flour: Principles and value in predicting flour functionality in different wheat-based food processes and in wheat breeding-A review. Cereal Chem. https://doi.org/10.1094/CCHEM-07-11-0092

Lau, S.K., Dag, D., Ozturk, S., Kong, F., Subbiah, J., 2020. A comparison between the open-ended coaxial probe method and the parallel plate method for measuring the dielectric properties of low-moisture foods. LWT. https://doi.org/10.1016/j.lwt.2020.109719

Lau, S.K., Thippareddi, H., Jones, D., Negahban, M., Subbiah, J., 2016. Challenges in

Radiofrequency Pasteurization of Shell Eggs: Coagulation Rings. J. Food Sci. 81, E2492–E2502. https://doi.org/10.1111/1750-3841.13440

Li, Y.C., Chen, S. Der, Yao, M.C., 2015. Effects of radio frequency heating on disinfestation and sterilization of rice flour. Taiwan. J. Agric. Chem. Food Sci. https://doi.org/10.6578/TJACFS.2015.014

Liu, S., Ozturk, S., Xu, J., Kong, F., Gray, P., Zhu, M.J., Sablani, S.S., Tang, J., 2018. Microbial validation of radio frequency pasteurization of wheat flour by inoculated pack studies. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2017.08.013

Liu, Y., Tang, J., Mao, Z., 2009. Analysis of bread dielectric properties using mixture equations. J. Food Eng. 93, 72–79. https://doi.org/10.1016/j.jfoodeng.2008.12.032

Los, A., Ziuzina, D., Bourke, P., 2018. Current and Future Technologies for Microbiological Decontamination of Cereal Grains. J. Food Sci. https://doi.org/10.1111/1750-3841.14181

McCormick, K.M., Panozzo, J.F., Hong, S.H., 1991. A swelling power test for selecting potential noodle quality wheats. Aust. J. Agric. Res. 42, 317–323. https://doi.org/10.1071/AR9910317

Oh, I.K., Bae, I.Y., Lee, H.G., 2018. Effect of dry heat treatment on physical property and in vitro starch digestibility of high amylose rice starch. Int. J. Biol. Macromol. 108, 568–575. https://doi.org/10.1016/J.IJBIOMAC.2017.11.180

Ozturk, S., Kong, F., Singh, R.K., Kuzy, J.D., Li, C., 2017a. Radio frequency heating of corn flour: Heating rate and uniformity. https://doi.org/10.1016/j.ifset.2017.05.001

Ozturk, S., Kong, F., Singh, R.K., Kuzy, J.D., Li, C., 2017b. Radio frequency heating of corn

flour: Heating rate and uniformity. Innov. Food Sci. Emerg. Technol. 44, 191–201. https://doi.org/10.1016/j.ifset.2017.05.001

Parinyasiri, T., Chen, T.C., Reed, R.J., 1991. YIELDS and BREADING DISPERSION of CHICKEN NUGGETS DURING DEEP-FAT FRYING AS AFFECTED BY PROTEIN CONTENT of BREADING FLOUR. J. Food Process. Preserv. https://doi.org/10.1111/j.1745-4549.1991.tb00179.x

Piyasena, P., Dussault, C., Koutchma, T., Ramaswamy, H.S., Awuah, G.B., 2003. Radio Frequency Heating of Foods: Principles, Applications and Related Properties - A Review. Crit. Rev. Food Sci. Nutr. https://doi.org/10.1080/10408690390251129

Ran, X. li, Zhang, M., Wang, Y., Liu, Y., 2019. Vacuum radio frequency drying: a novel method to improve the main qualities of chicken powders. J. Food Sci. Technol. 56, 4482–4491. https://doi.org/10.1007/s13197-019-03933-0

Saiz, A.I., Manrique, G.D., Fritz, R., 2001. Determination of Benzoyl Peroxide and Benzoic Acid Levels by HPLC during Wheat Flour Bleaching Process. https://doi.org/10.1021/jf9912304

Saka, I., Topcam, H., Son, E., Ozkaya, B., Erdogdu, F., 2021. Effect of radio frequency processing on physical, chemical, rheological and bread-baking properties of white and whole wheat flour. LWT 147, 111563. https://doi.org/10.1016/j.lwt.2021.111563

Schofield, J.D., Bottomley, R.C., Timms, M.F., Booth, M.R., 1983. The effect of heat on wheat gluten and the involvement of sulphydryl-disulphide interchange reactions. J. Cereal Sci. 1, 241–253. https://doi.org/10.1016/S0733-5210(83)80012-5

Senanayake, S., Gunaratne, A., Ranaweera, K., Bamunuarachchi, A., 2013. Effect of Heat

Moisture Treatment Conditions on Swelling Power and Water Soluble Index of Different Cultivars of Sweet Potato (Ipomea batatas (L). Lam) Starch 2013. https://doi.org/10.1155/2013/502457

Slaughter, D.C., Karl H. Norris, William R. Hruschka, 1992. Quality and classification of hard red wheat. Cereal Chem 69, 428–432.

Steertegem, B. Van, Pareyt, B., Slade, L., Levine, H., Brijs, K., Delcour, J.A., 2013a. Impact of Heat Treatment on Wheat Flour Solvent Retention Capacity (SRC) Profiles; Impact of Heat Treatment on Wheat Flour Solvent Retention Capacity (SRC) Profiles. https://doi.org/10.1094/CCHEM-04-13-0069-N

Steertegem, B. Van, Pareyt, B., Slade, L., Levine, H., Brijs, K., Delcour, J.A., 2013b. Impact of Heat Treatment on Wheat Flour Solvent Retention Capacity (SRC) Profiles; Impact of Heat Treatment on Wheat Flour Solvent Retention Capacity (SRC) Profiles. https://doi.org/10.1094/CCHEM-04-13-0069-N

Tan, C.P., Che Man, Y.B., Jinap, S., Yusoff, M.S.A., 2001. Effects of microwave heating on changes in chemical and thermal properties of vegetable oils. JAOCS, J. Am. Oil Chem. Soc. https://doi.org/10.1007/s11745-001-0418-5

Tiwari, G., Wang, S., Tang, J., Birla, S.L., 2011. Analysis of radio frequency (RF) power distribution in dry food materials. J. Food Eng. 104, 548–556. https://doi.org/10.1016/j.jfoodeng.2011.01.015

U.S. Food & Drug., 2019. Hometown Food Company Recalls Two Production LOT Codes of Pillsbury® Unbleached All-Purpose 5lb Flour Due to Possible Health Risk | FDA [WWW Document]. URL https://www.fda.gov/safety/recalls-market-withdrawals-

safety-alerts/hometown-food-company-recalls-two-production-lot-codes-pillsburyr-unbleached-all-purpose-5lb-flour (accessed 1.30.21).

USDA, 2020a. Flour, wheat, all-purpose, unenriched, unbleached [WWW Document]. URL https://fdc.nal.usda.gov/fdc-app.html#/food-details/790018/nutrients (accessed 6.23.21).

USDA, 2020b. Flour, wheat, all-purpose, enriched, bleached [WWW Document]. URL https://fdc.nal.usda.gov/fdc-app.html#/food-details/789890/nutrients (accessed 6.23.21).

USDA, 2017. Flour Tests : USDA ARS [WWW Document]. URL https://www.ars.usda.gov/midwest-area/wooster-oh/corn-soybean-and-wheat-quality-research/docs/flour-tests/ (accessed 6.21.21).

Uyar, R., Bedane, T.F., Erdogdu, F., Koray Palazoglu, T., Farag, K.W., Marra, F., 2015. Radio-frequency thawing of food products - A computational study. J. Food Eng. https://doi.org/10.1016/j.jfoodeng.2014.08.018

Vadivambal, R., Jayas, D.S., 2010. Non-uniform temperature distribution during microwave heating of food materials-A review. Food Bioprocess Technol. 3, 161–171. https://doi.org/10.1007/s11947-008-0136-0

VanCauwenberge, J.E., Bothast, R.J., Kwolek, W.F., 1981. Thermal inactivation of eight Salmonella serotypes on dry corn flour. Appl. Environ. Microbiol. 42, 688–691. https://doi.org/10.1128/aem.42.4.688-691.1981

Wang, S., Monzon, M., Johnson, J.A., Mitcham, E.J., Tang, J., 2007. Industrial-scale radio frequency treatments for insect control in walnuts I: Heating uniformity and energy efficiency. Postharvest Biol. Technol. 45, 240–246. https://doi.org/10.1016/j.postharvbio.2006.12.023

Wang, S., Yue, J., Tang, J., Chen, B., 2005. Mathematical modelling of heating uniformity for in-shell walnuts subjected to radio frequency treatments with intermittent stirrings. Postharvest Biol. Technol. 35, 97–107. https://doi.org/10.1016/J.POSTHARVBIO.2004.05.024

Wang, Y., Zhang, L., Johnson, J., Gao, M., Tang, J., Powers, J.R., Wang, S., 2013. Developing Hot Air-Assisted Radio Frequency Drying for In-shell Macadamia Nuts. Food Bioprocess Technol. 7, 278–288. https://doi.org/10.1007/s11947-013-1055-2

Wu, S., Ricke, S.C., Schneider, K.R., Ahn, S., 2017. Food safety hazards associated with ready-to-bake cookie dough and its ingredients. Food Control. https://doi.org/10.1016/j.foodcont.2016.10.010

Xiao, Z.S., Park, S.H., Chung, O.K., Caley, M.S., Seib, P.A., 2006. Solvent retention capacity values in relation to hard winter wheat and flour properties and straight-dough breadmaking quality. Cereal Chem. 83, 465–471. https://doi.org/10.1094/CC-83-0465

Yu, D.U., Shrestha, B.L., Baik, O.D., 2015. Radio frequency dielectric properties of bulk canola seeds under different temperatures, moisture contents, and frequencies for feasibility of radio frequency disinfestation. Int. J. Food Prop. https://doi.org/10.1080/10942912.2015.1013630

Zhang, S., Huang, Z., Wang, S., 2017. Improvement of radio frequency (RF) heating uniformity for peanuts with a new strategy using computational modeling. Innov. Food Sci. Emerg. Technol. https://doi.org/10.1016/j.ifset.2017.02.009

Zheng, A., Zhang, B., Zhou, L., Wang, S., 2016. Application of radio frequency pasteurization to corn (Zea mays L.): Heating uniformity improvement and quality

stability evaluation. J. Stored Prod. Res. https://doi.org/10.1016/j.jspr.2016.04.007

Zhou, L., Wang, S., 2016. Industrial-scale radio frequency treatments to control Sitophilus oryzae in rough, brown, and milled rice. https://doi.org/10.1016/j.jspr.2016.03.002

Zhu, H. kun, Yang, L., Fang, X. fa, Wang, Y., Li, D., Wang, L. jun, 2021. Effects of intermittent radio frequency drying on structure and gelatinization properties of native potato flour. Food Res. Int. 139, 109807. https://doi.org/10.1016/j.foodres.2020.109807

Appendices

Table 3.1 Proximate analysis for the unprocessed bleached and unbleached all-purpose flours

	Flour type and condition	
Proximate analysis	**Unbleached flour**	**Bleached flour**
Moisture content (%, d.b.)	13.90 ± 0.0005	12.94 ± 0.001
Water activity	0.36 ± 0.01	0.24 ± 0.004
Protein content (%)	12.27 ± 0.24	9.96 ± 0.04
Crude fat content (%)	0.57 ± 0.10	0.59 ± 0.13
Ash content (%)	0.51 ± 0.0001	0.57 ± 0.0004

Table 3.2 Color values (L*, a*, b*) of the unbleached and bleached all-purpose flour after various RF assisted processing conditions

Flour Type	Condition	Color value					
		L*		a*		b*	
Unbleached flour	Unprocessed	86.53	± 0.27	0.46	± 0.05	9.50	± 0.25
	RF 80°C	86.42	± 0.45	0.33	± 0.04	9.38	± 0.34
	RF&A 80°C	86.90	± 0.26	0.22	± 0.04	9.69	± 0.21
	RF 85°C	86.76	± 0.56	0.36	± 0.04	10.24	± 0.35
	RF&A 85°C	86.58	± 0.61	0.28	± 0.03	10.34	± 0.25
	RF 90°C	86.31	± 0.40	0.34	± 0.02	9.58	± 0.12
	RF&A 90°C	85.22	± 0.58	0.24	± 0.04	10.35	± 0.32
Bleached flour	Unprocessed	87.94	± 0.51	0.37	± 0.04	9.77	± 0.38
	RF 80°C	87.12	± 0.32	0.27	± 0.02	8.38	± 0.11
	RF&A 80°C	86.80	± 0.57	0.26	± 0.03	8.78	± 0.27
	RF 85°C	87.06	± 0.53	0.36	± 0.04	9.90	± 0.35
	RF&A 85°C	86.59	± 0.37	0.28	± 0.04	9.46	± 0.46
	RF 90°C	86.87	± 0.48	0.23	± 0.02	8.84	± 0.18
	RF&A 90°C	86.62	± 0.28	0.22	± 0.04	9.31	± 0.20

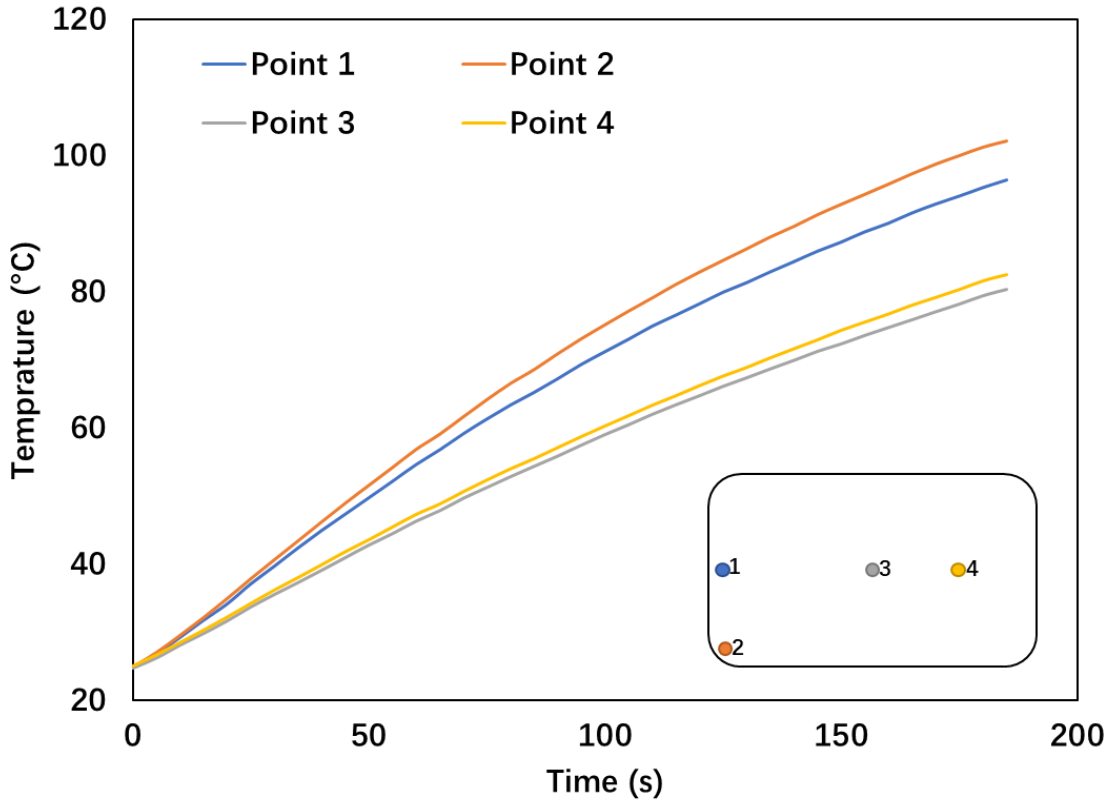


Figure 3.1. Temperature profiles of unbleached flour during RF heating process. The fiber thermocouples were locate at 4 different location of the sample cross-section of the geometry.

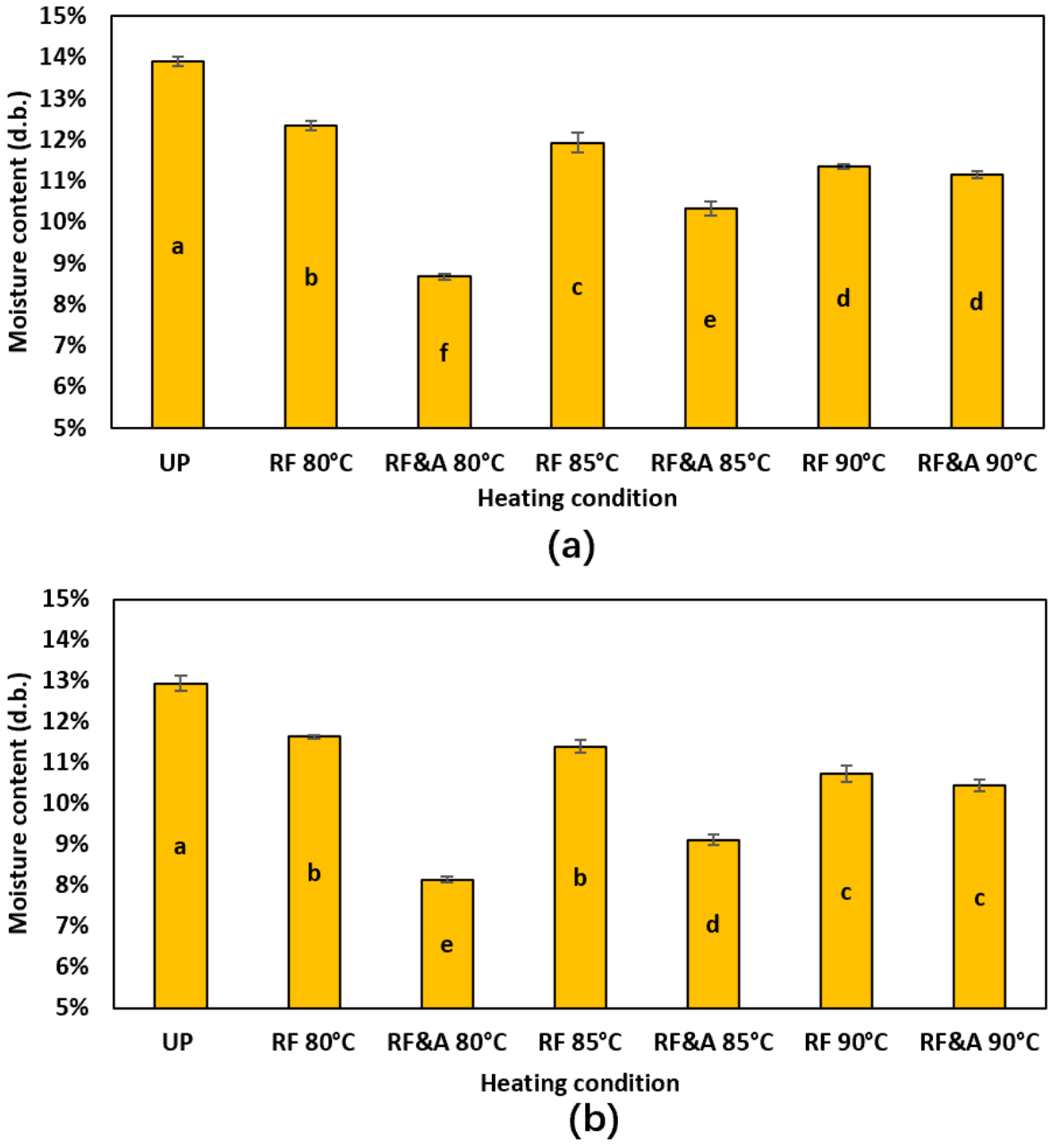


Figure 3.2. Moisture contents of the unbleached flour (a) and bleached flour (b) after various RF assisted processing (Unprocessed flour (UP), RF preheating and RF-assisted hot air heating (RF&A). * Different letters in the figure indicate a significant difference ($p < 0.05$)).

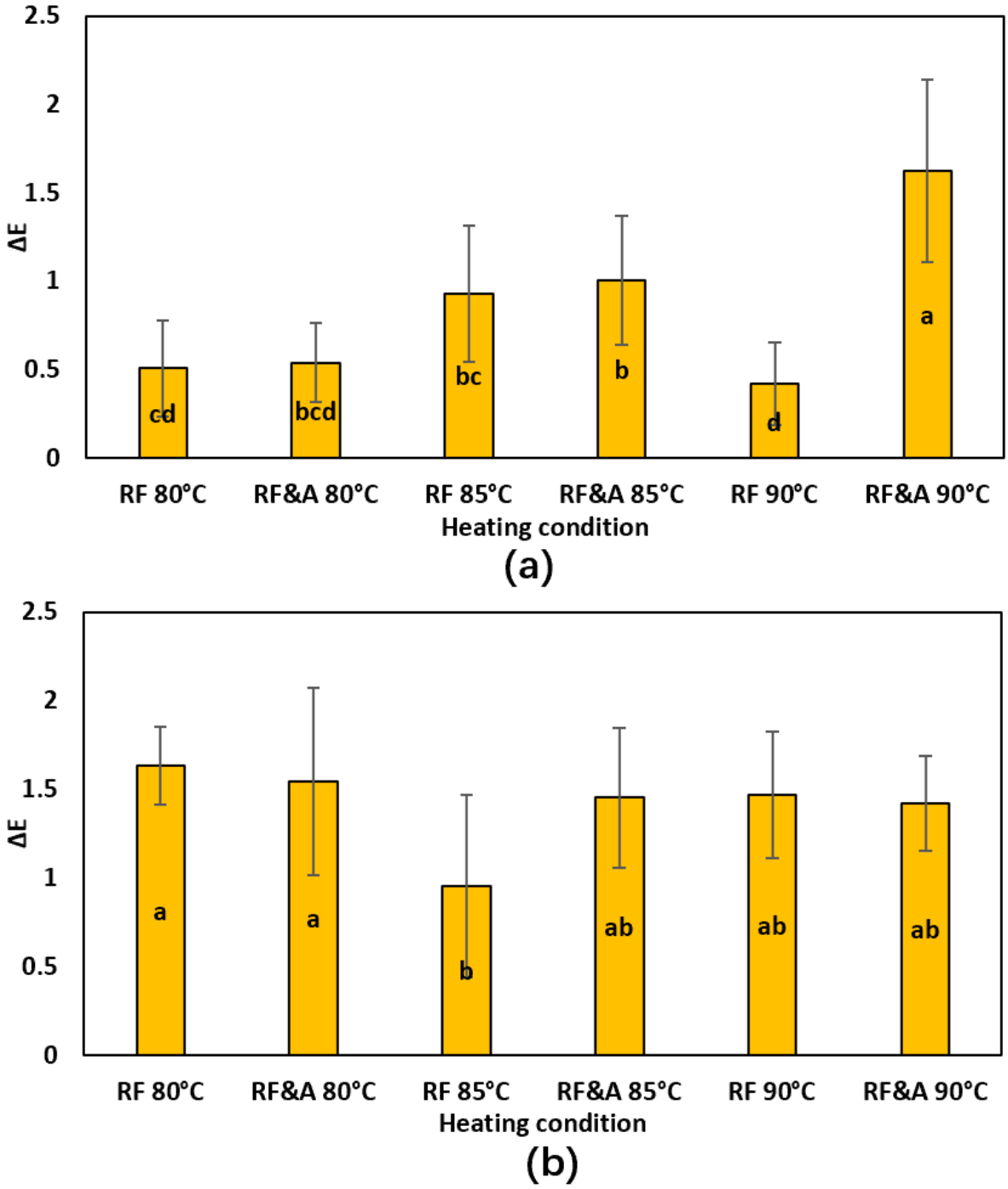
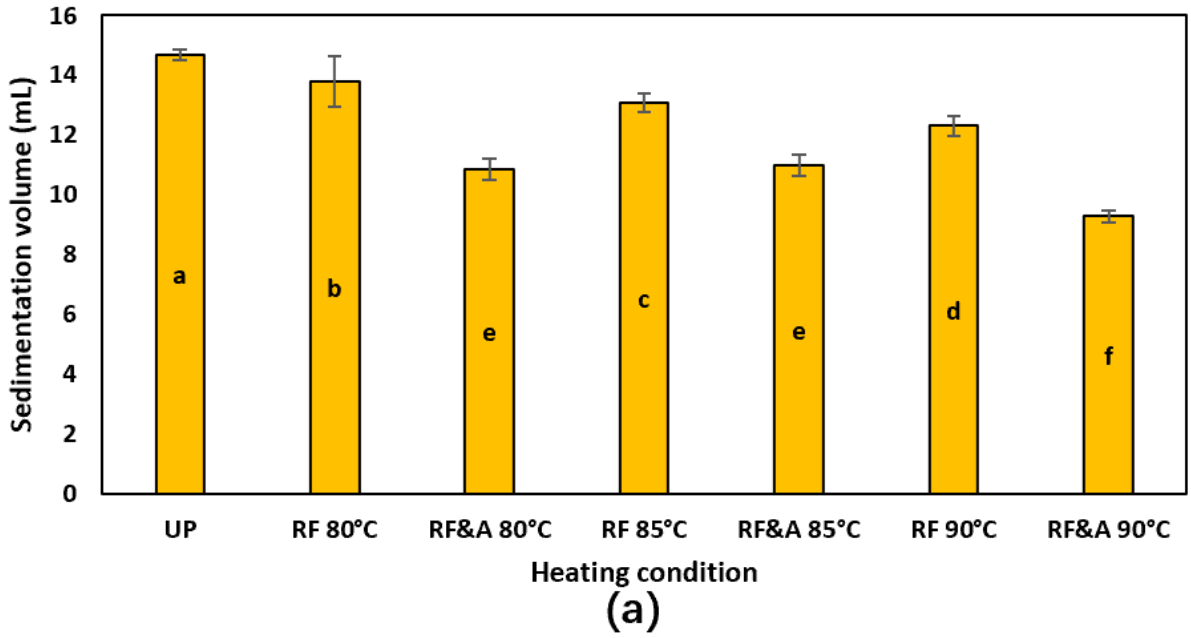


Figure 3.3. The total color difference (ΔE) results for unbleached flour (a) and bleached flour (b) (Unprocessed flour (UP), RF preheating and RF-assisted hot air heating (RF&A). * Different letters in the figure indicate a significant difference ($p < 0.05$)).



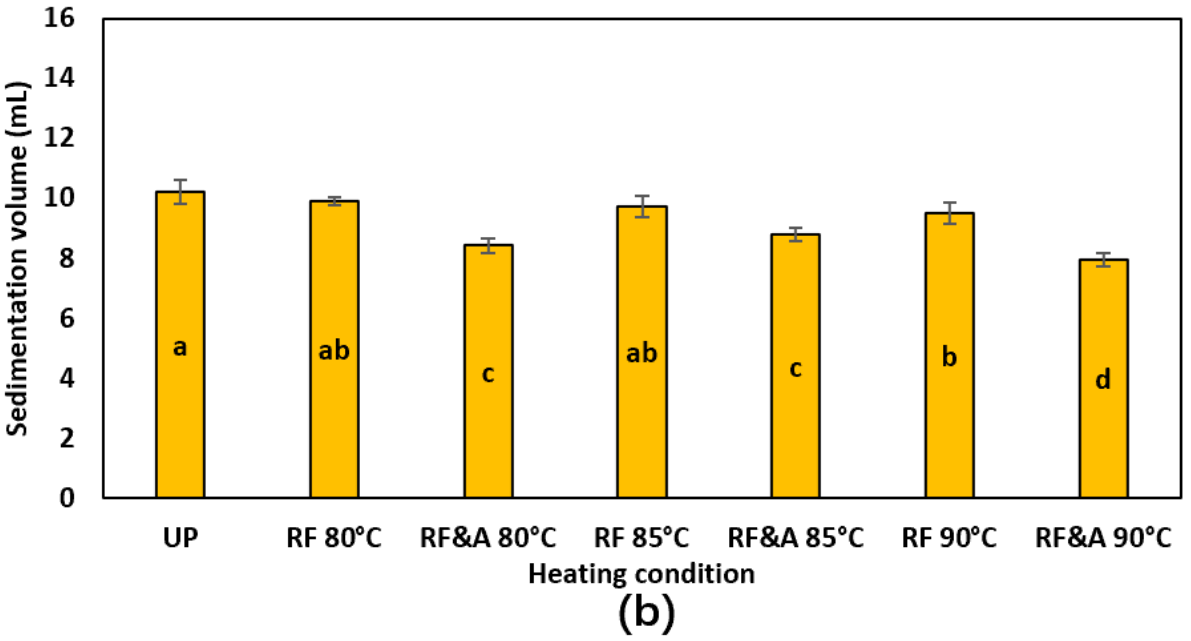


Figure 3.4. The SDS test results for the unbleached flour (a) and bleached flour (b) after various RF assisted processing (Unprocessed flour (UP), RF preheating and RF-assisted hot air heating (RF&A). * Different letters in the figure indicate a significant difference ($p < 0.05$)).

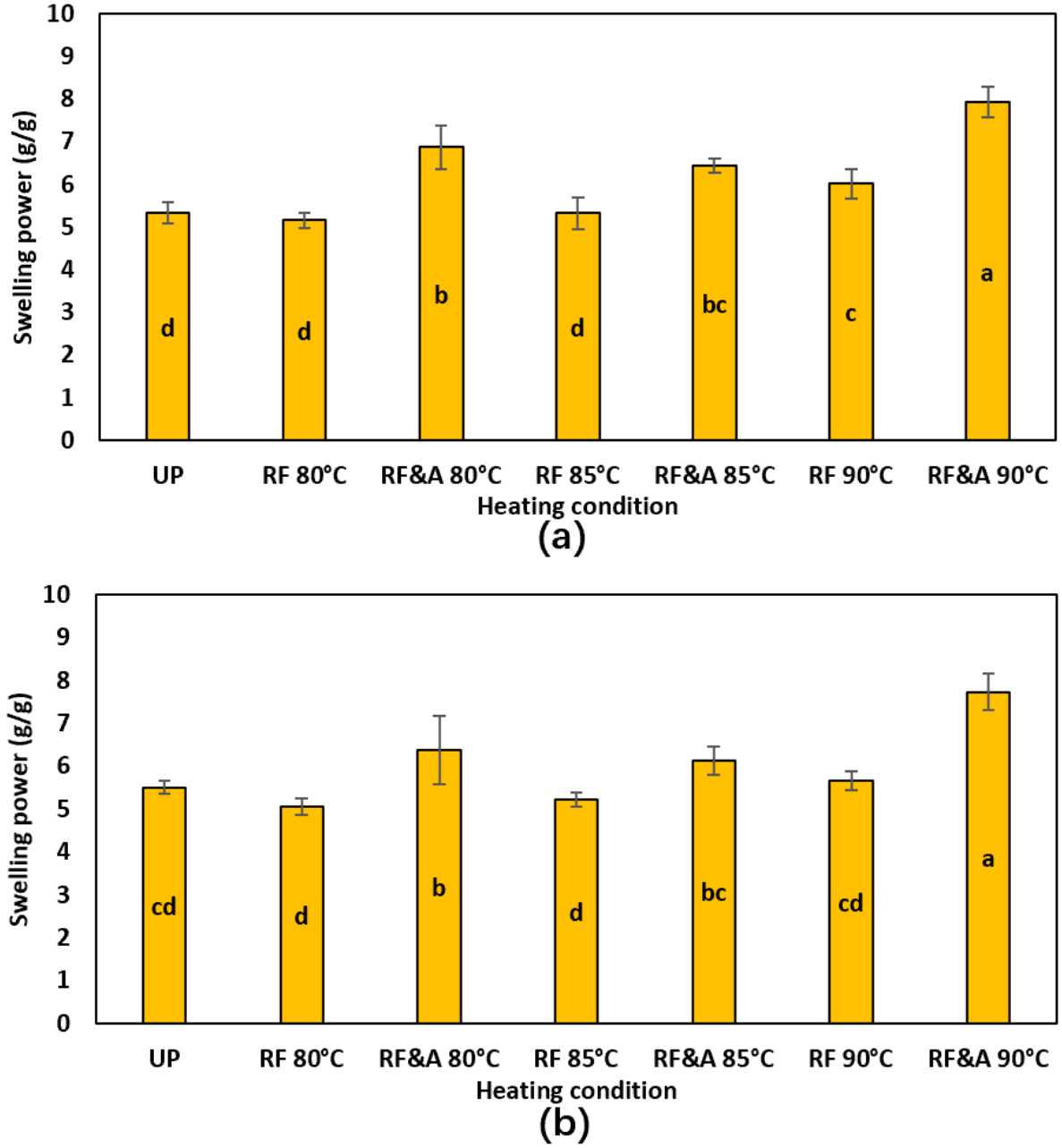


Figure 3.5. The Flour Swelling power for the unbleached flour (a) and bleached flour (b) after various RF assisted processing (Unprocessed flour (UP), RF preheating and RF-assisted hot air heating (RF&A). * Different letters in the figure indicate a significant difference ($p < 0.05$)).

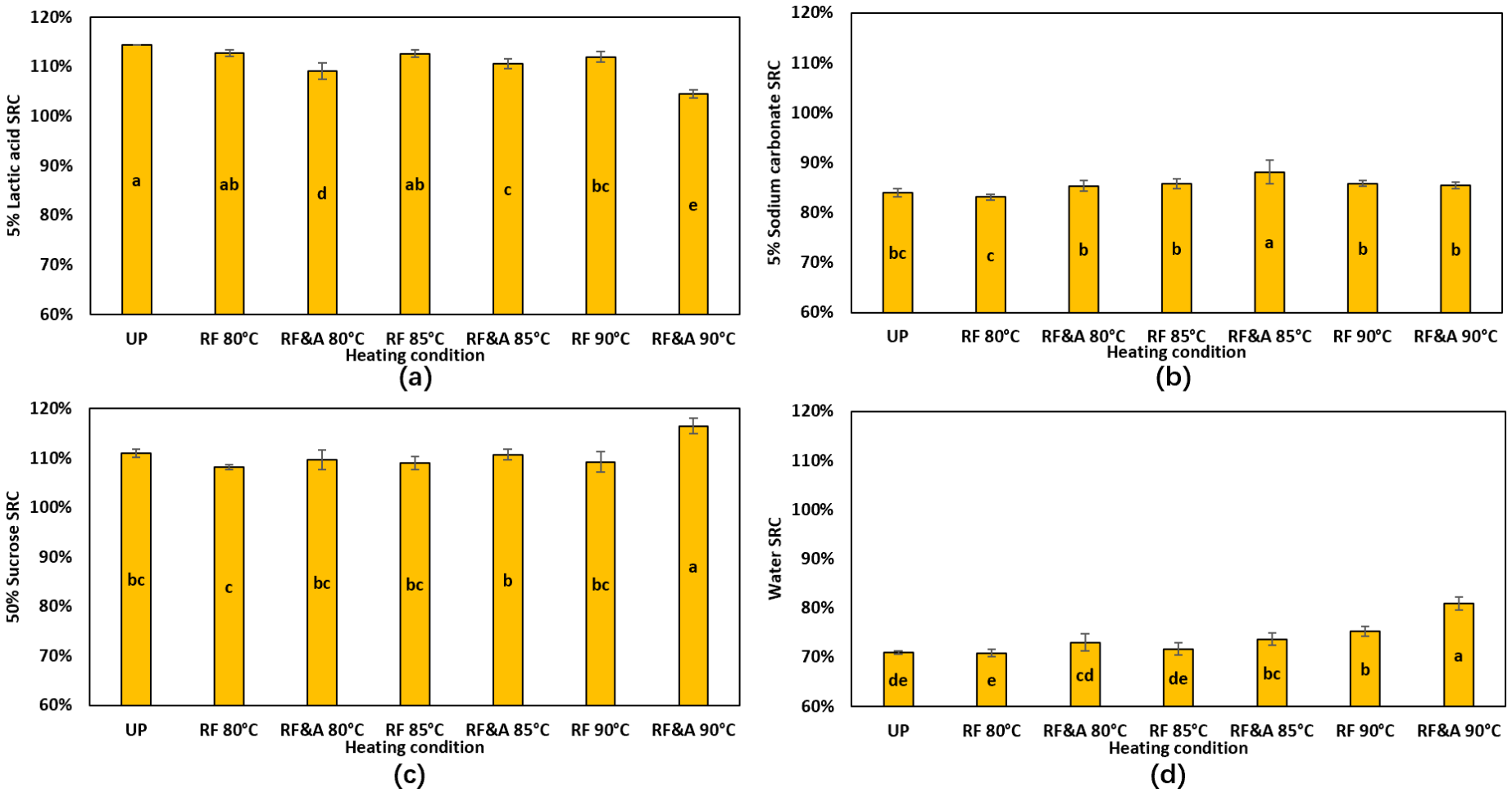


Figure 3.6. The SRC values in different solutions ((a) 5% lactic acid; (b) 5% sodium carbonate; (c) 50% sucrose; (d) water) for the unbleached flour after various RF assisted processing (Unprocessed flour (UP), RF preheating and RF-assisted hot air heating (RF&A). * Different letters in the figure indicate a significant difference ($p < 0.05$)).

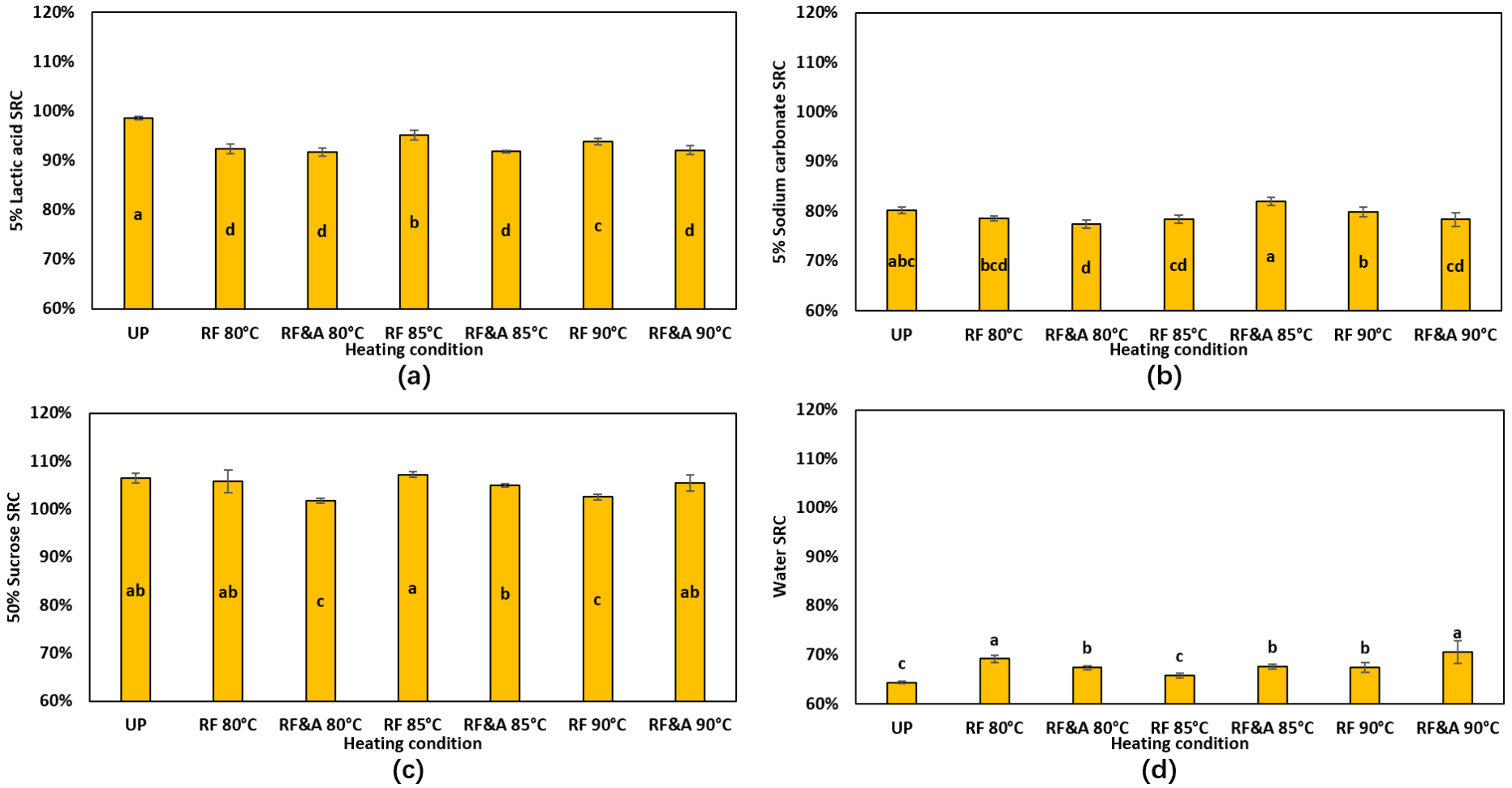


Figure 3.7. The SRC values in different solutions ((a) 5% lactic acid; (b) 5% sodium carbonate; (c) 50% sucrose; (d) water) for the bleached flour after various RF assisted processing (Unprocessed flour (UP), RF preheating and RF-assisted hot air heating (RF&A). * Different letters in the figure indicate a significant difference ($p < 0.05$)).

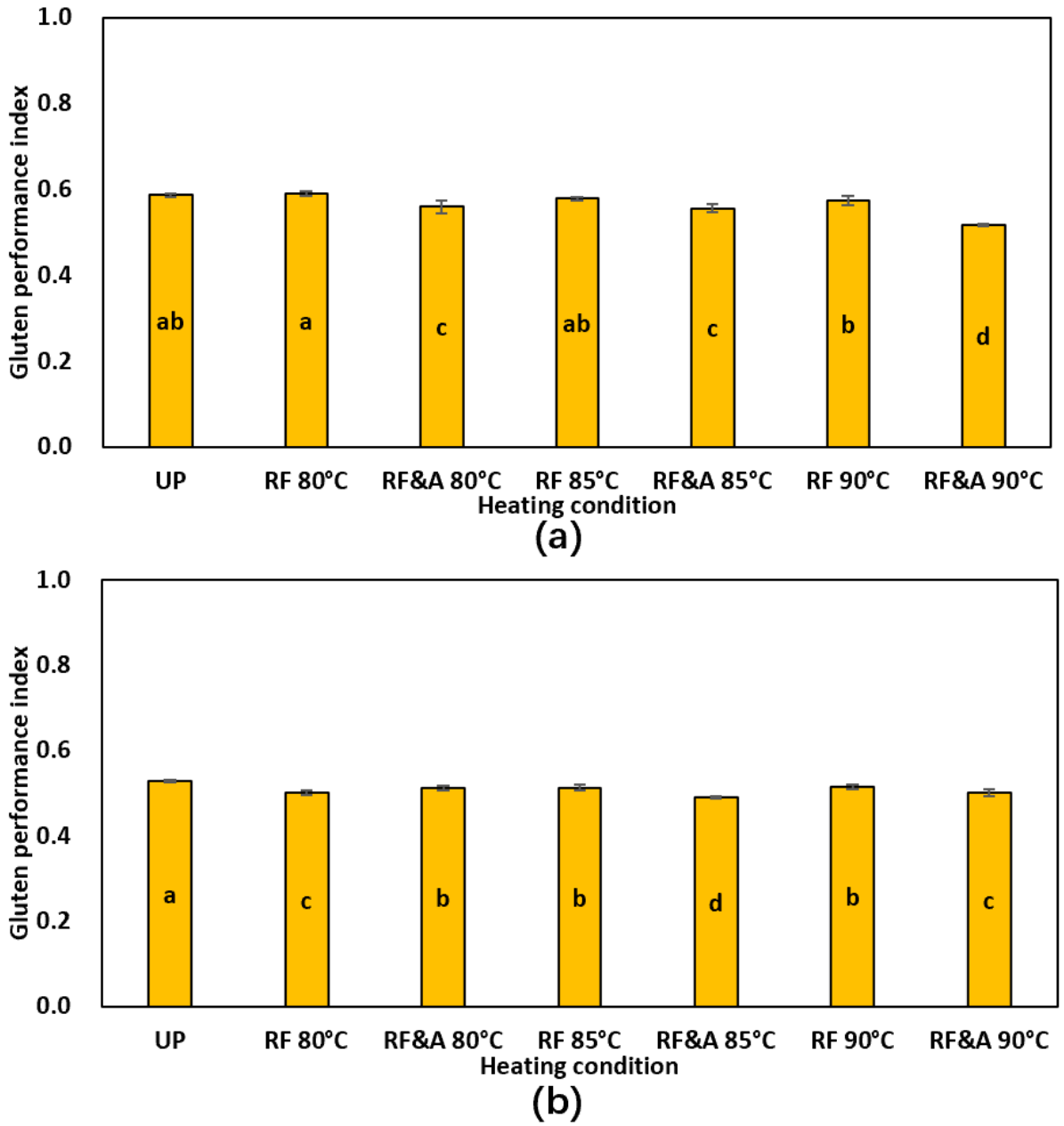


Figure 3.8. The GPI value for the unbleached flour (a) and bleached flour (b) after various RF assisted processing (Unprocessed flour (UP), RF preheating and RF-assisted hot air heating (RF&A). * Different letters in the figure indicate a significant difference ($p < 0.05$)).

Chapter 4

Summary and Recommendations for Future Work

4.1 Summary

Flour-based low moisture foods pose significant safety concerns to the consumer because pathogens can contaminate and survive in flours after post-harvesting and processing. RF heating is a promising technology to process the flours, but the knowledge gaps of non-uniform heating and quality change needed to be addressd.

This Thesis developed and used computer simulation models to demonstrated and understand the improvement of soybean oil medium on the RF heating pattern and heating rate. Since the dielectric constant of soybean oil is similar to the corn flour sample, the electric field distribution was unified to get a more even heating pattern. Also, the high electric potential gradient and low surface heat loss help increase the RF heating rate.

However, RF treatment may not maintain the quality and functionality of flour samples; especially like the all-purpose flour, which is high in protein content and starch damage content. This thesis also evaluated the quality and functional properties of bleached and unbleached wheat flour after RF heating and RF&A. Overall, the RF&A in different conditions tended to make significant changes in the quality and functionality of all the all-purpose flours (unbleached and bleached), but most of the quality changes were in the practical range. Besides, more influences were observed in the flour quality after the RF&A treatment than the RF treatment, and the bleached flour tends to have a less significant change than the unbleached flour.

4.2 Recommendations for future work

Some future work can focus on further improving the modeling accuracy and using modeling tools to design better RF processes. In modeling RF heating process, the dielectric property is an essential property to support the modeling results accuracy and has the possibility to improve. Besides, the modeling tools can be further used to design better RF processes. For example, it may be helpful to investigate the effect of medium heights and materials (e.g., different oils) on RF heating performance.

VITA

Qianyi Chen was born in Guangzhou, China on June 12, 1997. She graduated from University of Nebraska, Lincoln and received her Bachelor's degree in Food Science and Technology in 2019. Then, she pursue a Master of Science degree in Food Science at the University of Tennessee, Knoxville . Her research area is at the multiphysics modeling of the radio frequency heating and quality analysis of low moisture foods.