Continuous Radiofrequency-Assisted Thermal Processing of Packaged Soft Wheat Flour

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Authors’ contributions

This work was carried out in collaboration between both authors. SRB designed the experiments, performed all the experiments and wrote the first draft of the manuscript. JS was the principal investigator, provided the expertise in radiofrequency processing and supervised SRB work. Both authors read and approved the final manuscript.

Article Information

DOI: 10.9734/CJAST/2020/v39i3231004

Editor(s):
(1) Dr. Chen Chin Chang, Hunan Women’s University, China.

Reviewers:
(1) Hope Baloyi, Nelson Mandela University, South Africa.
(2) Sadia Aslam, Government College Women University Faisalabad, Pakistan.

Complete Peer review History: http://www.sdiarticle4.com/review-history/61919

Received 01 August 2020
Accepted 07 October 2020
Published 23 October 2020

Original Research Article

ABSTRACT

Soft wheat flour (SWF) is a low-moisture food ingredient in many ready-to-eat foods. Foodborne illnesses and outbreaks from consumption of multiple low-moisture foods heightened the importance of its microbiological safety. Traditional thermal processing methods take a long time to achieve desired pasteurization and are not suitable for processing the packaged products. The novel continuous radiofrequency (RF)-assisted thermal processing for packaged SWF was investigated with an objective of reducing the processing time. The temperature profiles in packaged SWF during RF heating at eight different locations under the stationary and moving conditions were investigated. The temperature difference between the coldest and the hottest locations in stationary RF heating of packaged SWF was 31°C. When the package was flipped up-side down along the long axis in stationary condition, the temperature difference was reduced to 24°C. The RF heating uniformity of packaged SWF with the conveyor movement improved and the temperature difference between the hottest and the coldest locations under this condition was only 15°C. The quality parameters of packaged SWF at 80°C for 7 h were not significantly different from that of the unpasteurized and batch mode processed SWF. This study demonstrated the continuous RF-assisted thermal processing of packaged SWF.

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Keywords: Come-up time; cookie quality; heating uniformity; heat treatment; rapid-visco-analyzer.

1. INTRODUCTION

Soft wheat flour (SWF), a low-moisture food product, is an ingredient in many ready-to-eat foods. Foodborne illnesses and outbreaks from the consumption of multiple low-moisture foods heightened the importance of pasteurizing the low moisture foods [1,2,3]. Traditional thermal processing methods take a long time to achieve desired pasteurization in low-moisture foods because of low thermal conductivity and high thermal resistance of the foodborne pathogens under the low moisture environments. These methods have the limitation of treating the flours in bulk and are not suitable to process the packaged products. The package pasteurization prevents cross contamination of the products in an industrial environment. A novel radiofrequency (RF)-assisted thermal processing of SWF with an objective of reducing the come-up time (time taken to raise the product’s temperature at the coldest location to the desired process temperature) was demonstrated in a batch mode under the laboratory conditions [4]. The quality and functionality of batch mode processed SWF at 80°C for 7 h and 90°C for 2 h were not significantly different from that of the unpasteurized SWF. The above recommended temperature and time combinations were estimated to achieve a minimum of 7 log reductions of Salmonella spp. in SWF. Those studies were investigated with relatively small amount of SWF in a cylindrical polypropylene container under the stationary condition. The present study focused on continuous RF-assisted thermal processing of the packaged SWF. As the product packaging conditions are different, it is expected to have different temperature distribution and heating uniformity within the packaged product. The evaluation of quality and functionality of processed SWF is a vital for final adoption of this method by the industry.

The RF heating method heats the product volumetrically and rapidly due to friction resulting from rotational movement of the molecules and ions (space charge) in an alternating electric field at radiofrequencies. Hence, RF-heating is primarily targeted to reduce the come-up time. RF waves can heat the packaged products as packaging materials such as paper and polyethylene are permeable to radio waves. Therefore, the RF-assisted thermal processing of packaged products is feasible. If pasteurization of the low-moisture foods could be achieved in packaging conditions, then cross-contamination can be eliminated. RF heating method is also known for its non-uniform heating if the RF heating system does not match with the product packaging configuration. Similar to microwave heating, cold and hot spots exist in RF heating too. The heating uniformity in the food matrix depends on electrode configuration, container or packaging geometry, food dielectric properties, and surrounding medium [5,6,7,8,9,10]. However, the non-uniform heating can be minimized by selecting the proper RF electrode configuration and product configurations (size and shape). Hence, the product temperature profiles under the RF heating are important to know the coldest and the hottest locations within the food matrix. These profiles also warrant the microbiological safety of the processed foods. Because the microbiological safety of the foods depends on the coldest location of the food being heated, identification and heating of the coldest location is a vital need. An experimental study to validate the microbial rate kinetics in continuous radio-frequency assisted thermal processing pasteurization of egg white powder was conducted [11]. Computer simulation model for RF-heating of the wheat flour in a stationary rectangular container was also developed [12,13]. Numerical microwave models were developed to simulate the sterilization of packaged product and validated with the homogeneous whey protein gel by some other researchers [14]. To our knowledge none of the studies reported the RF-assisted thermal processing of packaged low-moisture food products. Hence, the objectives of the present study were to: (1) determine the process parameters (electrode gap and belt speed) for continuous RF-assisted thermal processing of packaged SWF, (2) obtain temperature profiles and evaluate the heating uniformity in packaged SWF, and (3) evaluate the quality and functionality of the continuous RF-assisted thermally processed packaged SWF.

2. MATERIALS AND METHODS

2.1 Material Procurement and Package Preparation

SWF samples were procured locally from Ardent Mills, Omaha, Nebraska, USA immediately after milling. The moisture content of SWF was 8.86%
2.3 Come-up Time at the Center of the Packaged Soft Wheat Flour during RF Heating and Hot Air Oven Heating

The suitable electrode gap for RF heating of the packaged SWF was determined by placing packaged SWF (910 g) inside the RF heater on a conveyor belt at the center of the bottom (ground) electrode. The packaged SWF was held in stationary condition on a conveyor belt. Eight fiber optic temperature probes (Neoptix, Inc., Quebec City, Quebec, Canada) were inserted at the geometric center (top, center, and bottom layers on the vertical axis) and at the edges in three layers of the packaged SWF as shown in the Fig. 1. The temperature raise in a packaged product at different eight locations during RF heating was monitored. Smaller the electrode gap, faster the heating rate. The electrode spacing was chosen by conducting trial-and-error method such that the RF power coupling was maximum (high heating rate). The RF power was supplied until the temperature at the coldest location of packaged SWF was raised to 100°C. Then, the heating uniformity within the package was determined by analyzing the temperature profiles. The temperature difference between the coldest and the hottest locations within the packaged SWF was considered as the heating uniformity. Similarly, the temperature raise at the center of SWF package in a hot air oven (Model: 28, Precision Scientific Group, Chicago, Ill.) was also investigated. The temperature profiles and time taken to raise the temperature to 100°C at geometric center of packaged SWF in both the heating conditions were compared. To improve the heating uniformity within the packaged product during RF heating, the package was flipped halfway during RF heating. The heating uniformity under the flipped condition was also determined from the temperature profiles.

2.4 RF Heating of the Packaged Soft Wheat Flour with Conveyor Movement

The time needed to raise the packaged SWF at the coldest location from room temperature (about 23°C) to 100°C specific to the particular electrode gap in the RF heating unit was determined from the above experiments. The conveyor belt speed was set to achieve the residence time based on the time requirements. The set-belt speed was specific to a particular electrode gap in a RF heating unit for stationary conditions. The temperatures in the packaged SWF were monitored and the conveyor speed was adjusted in such a way that the coldest location in the packaged SWF was heated to 100°C while the package moved from right to left side of the top electrode. Similar to the above stationery experiment, eight fiber optic temperature probes were inserted into the packaged SWF at different locations (Fig. 1). After inserting into packaged SWF, the probes were secured on a conveyor belt with an adhesive tape to prevent the distortion of the probe locations due to travel along the package. The temperature profiles in SWF during conveyor movement were monitored at eight different locations and used for heating uniformity evaluation.

2.5 Continuous RF-assisted Thermal Processing of Packaged Soft Wheat Flour

In RF-assisted thermal processing, RF heating unit is primarily used to pre-heat the food product to desired temperature and then the food product is held at that desired temperature for a desired time in a hot air oven or hot room. The temperature profiles of packaged SWF during
continuous RF heating and immediately transferring to a hot air oven were monitored. Two different locations inside the packaged SWF along the central axis of package i.e., one at the top layer (location 1 as shown in the Fig.1) which was the coldest location under the stationary condition and another one at the geometric center (location 2 as shown in the Fig.1) were chosen for this purpose. The two fiber optic temperature probes were inserted into the packaged product and secured on a belt to prevent distortion of probe locations during RF heating. The packaged SWF was RF-heated from room temperature to the desired temperature of 80°C while the product was moved on a conveyor belt. Then the product was moved to a hot air oven pre-set at that temperature. Another set of fiber optic temperature probes were inserted into a pre-heated packaged SWF immediately after placing in a hot air oven and monitored the temperatures at the locations 1 and 2 for 7 h. The processed package was placed inside a polythene storage bag and allowed to cool to the room temperature in a sealed condition. Then the package was opened and SWF was transferred into a bag. Three replicated samples were prepared and used for evaluation of quality.

2.6 Quality and Functionality Assessment of Continuous RF-assisted Thermally Processed Packaged Soft Wheat Flour

The quality and functionality of continuous RF-assisted thermally processed packaged SWF at 80°C for 7 h were assessed to determine the effect of the process. The quality such as color and functionality such as pasting properties (Rapid-Visco-Analyzer) of SWF were evaluated following the standard methods. The detailed description of the methods followed may be found elsewhere [4]. The triplicated samples were used for quality and functionality assessment. The quality and functionality values obtained were compared with that of the batch mode processed and unpasteurized SWF (control).

3. RESULTS AND DISCUSSION

3.1 Come-up Time at the Center of the Package during RF Heating and Hot Air Oven Heating

Fig. 2 shows the temperature profiles of packaged SWF under the RF heating and the hot air oven heating conditions. The RF heating of packaged SWF took about 6.5 min to raise from room temperature to 100°C at the geometric center (2) (Fig.2a). The time taken to raise the temperature at the coldest location (1, top center) to 100°C was approximately 8 min. The electrode gap in RF heating unit was 130 mm. The electrode gap was selected to have maximum heating rate in the product without any arcing.

As shown in the Fig. 2b, for the same package configuration and sample mass, the times required to raise the packaged SWF from room temperature to 80°C and 90°C were 8.5 h and 14 h, respectively in a hot air oven. Initially, the temperature of packaged SWF increased rapidly up to 70°C due to higher temperature gradient. However, the packaged SWF temperature did not reach to 100°C in a hot air oven maintained at 101°C even after 24 h heating. The RF power could heat packaged SWF very rapidly. Hence, RF power may be used to reduce the come-up time of the packaged SWF.

Fig. 2a presents the temperature profiles in packaged SWF at eight different locations under no movement (stationary) condition. In the stationary condition, center top (1) was the coldest location and the edges of the package were the hottest locations when heated to 100°C. The measured temperature difference along the central axis of the package (1 and 3) was about 15°C. However, the measured temperature difference between the hottest locations (edges and corners) and the coldest location under the stationary RF heating was about 31°C. Though the experimentally measured temperature difference between the hottest and the coldest locations of the package was about 31°C, the actual temperature difference between the coldest and the hottest locations could be more than the measured value. Due to the practical limitations, to have good contact between the fiber optic temperature probes and packaged SWF, the probes were inserted 10 mm deep inside the packaged product at the edges. From the temperature profiles under stationary condition, the time required to heat the packaged SWF to 100°C was about 8 min.

The packaged SWF was flipped upside down halfway when all the locations in package reached to 60°C with an objective of improving the heating uniformity. Under the flipped condition, similar to no flipping condition, the coldest and the hottest locations remained to be
center top (1) and the edges of the package when heated to 100°C. However, the measured temperature difference along central axis of the package (1 and 3) and between the hottest and the coldest locations were decreased. The measured temperature difference in central axis of the package was about 9°C. The measured temperature difference from the hottest locations (edges and corners) to the coldest location was 24°C. The flipping of the package helped to decrease the temperature difference between the coldest and the hottest locations about 6°C. The manual flipping of the package inside the RF heating oven took about 30-40 s.

![Fig. 1. Different locations monitored for the temperature raise in packaged soft wheat flour package](image)

![Graph showing temperature increase over time](image)
obtained at two different locations on central axis improved the heating uniformity by reducing the difference between the hottest edges to the locations 1 and 3 and temperature difference along the geometric central axis was 10°C. The temperature difference among the edges was 8°C. The temperature difference between the hottest edges to the coldest center was 16°C. The RF heating of packaged SWF under the movement condition improved the heating uniformity by reducing the temperature difference of 15°C between the hottest and the coldest locations.

3.2 RF Heating of the Packaged Soft Wheat Flour with Conveyor Movement

The conveyor belt speed of 8.2 m/h was chosen to heat the packaged SWF. With this belt speed and electrode gap of 130 mm, it took about 8 minutes to heat the packaged SWF from room temperature to 100°C (at the coldest location). The Fig. 3 shows the average temperature profiles at eight different locations of the packaged SWF under moving condition. Under the moving condition, the hottest locations were the center top (1). The temperature difference along the geometric central axis was 10°C (locations 1 and 3) and temperature difference among the edges was 8°C. The temperature difference between the hottest edges to the coldest center was 16°C. The RF heating of packaged SWF under the movement condition improved the heating uniformity by reducing the temperature difference of 15°C between the hottest and the coldest locations.

3.3 Continuous RF-assisted Thermal Processing of Packaged Soft Wheat Flour

Fig. 4 shows the typical temperature profiles obtained at two different locations on central axis (vertical) during the continuous RF-assisted thermal processing of packaged SWF at 80°C for 7 h. The straight lines portion at the starting of the temperature profiles represent the RF heating and remaining portion show the temperature profiles while maintaining the packaged SWF in a hot air oven. The temperature of packaged SWF was increased with RF power until the coldest location (center top) reached to 90°C. The desired process temperature was 80°C. The temperature after RF-heating was dropping to lower than 80°C when the packaged SWF was just RF-heated to 80°C and moved to a hot air oven for maintaining the temperature. It took a long time to increase the dropped product temperature to desired 80°C again. Hence, the packaged SWF was RF-heated to 10°C higher than the desired process temperature. Then the package was moved to a hot air oven immediately to maintain the desired product temperature. The hot air oven temperature was pre-set at 10°C higher than the desired temperature to prevent the drop in product temperature. The temperature profile at the geometric center of the product was initially higher and at the center top was lower. Eventually the trend flipped at about 100 min of storage in a hot air oven.
Fig. 3. Radiofrequency (RF) heating of soft wheat flour package while moving on a conveyor belt

The locations from (1) to (8) are shown in the Fig. 1

Fig. 4. Temperature profiles at two locations of the packaged soft wheat flour during continuous RF-assisted thermal processing

The temperature profiles demonstrated the feasibility of RF-assisted thermal processing of packaged SWF. This study used smaller retail sized packages compared to bigger 22.7 kg (50 lb) commercial packages. The temperature profiles in packaged SWF from this study may be used to validate the multiphysics based models. The validated models will be useful to study the RF heating of SWF in packages of different configuration (size and shape). These models also help in deciding the electrode configuration such as electrode length and shape needed for processing the commercial packages.
Table 1. Summary of quality and functionality parameters of soft wheat flour processed at different processing conditions

<table>
<thead>
<tr>
<th>Quality/functional parameter</th>
<th>'UP'</th>
<th>'TP'</th>
<th>80°C for 7 h 'RFA batch'</th>
<th>CRFA packaged</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final moisture content</td>
<td>8.8±0.4</td>
<td>7.4±0.3</td>
<td>8.1±0.5</td>
<td>3.2±1.2*</td>
</tr>
<tr>
<td>Color L*</td>
<td>95.1±0.5</td>
<td>94.0±0.7</td>
<td>94.9±0.2</td>
<td>95.3±0.2</td>
</tr>
<tr>
<td>a*</td>
<td>0.7±0.1</td>
<td>0.7±0.2</td>
<td>0.5±0.1</td>
<td>0.4±0.2</td>
</tr>
<tr>
<td>b*</td>
<td>7.4±0.8</td>
<td>7.6±0.2</td>
<td>7.3±0.6</td>
<td>6.5±0.2</td>
</tr>
<tr>
<td>ΔE</td>
<td>0.0±0.0</td>
<td>1.4±0.6</td>
<td>0.7±0.2</td>
<td>1.2±0.6</td>
</tr>
<tr>
<td>RVA Peak</td>
<td>233.2±4.1</td>
<td>239.3±5.7</td>
<td>249.8±3.2*</td>
<td>251.0±4.4*</td>
</tr>
<tr>
<td>Trough</td>
<td>159.9±6.7</td>
<td>154.8±3.5</td>
<td>168.1±3.3</td>
<td>136.7±12.0*</td>
</tr>
<tr>
<td>Breakdown</td>
<td>73.3±5.3</td>
<td>84.5±7.2</td>
<td>81.8±3.8</td>
<td>110.8±4.3*</td>
</tr>
<tr>
<td>Final</td>
<td>261.5±5.1</td>
<td>266.9±4.8</td>
<td>283.9±5.2</td>
<td>264.2±5.3</td>
</tr>
<tr>
<td>Setback</td>
<td>101.6±2.6</td>
<td>112.2±4.2*</td>
<td>115.8±5.6*</td>
<td>123.9±2.3*</td>
</tr>
<tr>
<td>Peak Time, min</td>
<td>6.3±0.0</td>
<td>6.2±0.1</td>
<td>6.2±0.0</td>
<td>6.0±0.1</td>
</tr>
<tr>
<td>Pasting Temp, °C</td>
<td>86.6±1.0</td>
<td>86.2±0.6</td>
<td>85.2±1.1</td>
<td>82.0±6.2</td>
</tr>
</tbody>
</table>

Note:

1. The values (except color) presented in these columns were obtained during the study conducted in batch mode for soft wheat flour [4].
2. The asterisk '*' in the shaded cell indicates the significant difference of the quality / functionality value when compared to that of the unpasteurized soft wheat flour (control).

3.4 Quality and Functionality of the Continuous RF-assisted Thermally Processed Packaged Soft Wheat Flour

The quality and functional properties of SWF processed at different treatment conditions are presented in Table 1. The average final moisture content of continuous RF-assisted thermally processed packaged SWF was 3.2±1.2% d.b. which is significantly different from that of all other processing conditions. The total loss in weight of SWF after processing at 80°C for 7 h was about 5.4% of its initial weight. The higher loss of moisture may be attributed to the packaging conditions. The low moisture content of the packaged soft flour influences the rheological properties of cookie dough [15].

The CIE Lab color values (L*, a* and b*) of package processed SWF at 80°C for 7 h were not significantly different from that of the unpasteurized SWF and batch mode processed SWF. The calculated total color difference (ΔE) was also < 2, which is ΔE tolerance limit [16]. Hence, it was concluded that the RF-assisted thermal processing did not adversely affect the color of the package processed SWF.

Rapid-Visco-Analyzer (RVA) pasting properties for the SWF processed at different processing conditions are also presented in Table 1. The final viscosity, which indicates the ability of the flour to form a viscous paste or gel after cooking and cooling [17], of the package processed SWF was not significantly different from that of the unpasteurized SWF. However, four of the RVA pasting properties (peak viscosity, trough viscosity, breakdown viscosity and setback viscosity) for the package processed SWF at 80°C for 7 h were significantly different from that of the unpasteurized SWF. The peak viscosity values indicate the water holding capacity of the starch present in the flour. The trough viscosity is the ability of the flour to withstand to constant temperature and shear stress. The breakdown viscosity is related to starch and higher values of breakdown viscosity are undesirable as higher values lead to uneven viscosity and cohesive nature of the paste. Setback viscosity involves the retro-gradation of the starch molecules and higher values are associated with syneresis or weeping during freezing or thawing of the end-products. The other RVA pasting parameters...
4. CONCLUSIONS

The continuous radiofrequency (RF)-assisted thermal processing of packaged SWF was investigated with an objective of reducing the come-up time and improving the microbiological safety. The come-up times of packaged SWF under RF heating and hot air oven heating conditions were determined. The temperature distribution profiles in packaged SWF under stationary condition and conveyor moving condition were investigated. The temperature difference between the coldest and the hottest location was 31°C in stationary RF heating of the packaged SWF. When the packaged SWF was flipped halfway to improve the heating uniformity, the temperature difference among the coldest and the hottest locations within the package was 24°C. The RF heating uniformity of packaged SWF under the conveyor movement condition was improved. The temperature difference between the hottest and the coldest locations under this condition was only 15°C. Most of the quality parameters for package processed SWF at 80°C for 7 h were not significantly different from that of the unpasteurized and batch mode processed SWF. This study demonstrated the continuous RF-assisted thermal processing of packaged SWF.

ACKNOWLEDGEMENTS

Funding for this study was received from Mussehl Poultry Foundation and USDA-NIFA award # 2014-67005-21734. We thank graduate colleagues Soon Kiat Lau and Dr. Krishnamoorthy Pitchai for help while conducting the experiments.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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