Progress In Electromagnetics Research B, Vol. 51, 201–220, 2013

EFFECT OF RADIOFREQUENCY HEATING ON THE DIELECTRIC AND PHYSICAL PROPERTIES OF EGGS

Shrikalaa Kannan[1], Satyanarayan R. S. Dev[2], Yvan Gariépy[1], and G. S. Vijaya Raghavan[1, *]

[1]Department of Bioresource Engineering, McGill University, 21111 Lakeshore Road, Sainte Anne de Bellevue, QC H9X 3V9, Canada

[2]Department of Food Science, A'Sharqiyah University, Ibra, Sultanate of Oman

Abstract—Eggs are one of the most nutritious foods available in nature. This rich nutritive environment attracts microbes to invade, feed and multiply. *Salmonella enteritidis* is one such microbe that is highly pathogenic and is the causative agent for the disease salmonellosis. To ensure safety of eggs, processing them without affecting their unique physical properties is essential. In this study, the impact of radiofrequency (RF) heating on the dielectric properties (dielectric constant and dielectric loss factor) of the egg at varying temperatures (5°C–56°C) and frequency (10 MHz–3 GHz) is evaluated. This study on the dielectric parameters is essential to devise a better heating paradigm wherein there is minimal detrimental effect to the egg components. Based on the dielectric study, the heating process parameters were determined. The effect of such heat treatment on the physical properties viz. Viscosity, foam density, foam stability and turbidity of the egg white were also studied. This study was conducted to provide sufficient literature and experimental background for employing RF in pasteurization of in-shell eggs. This study showed that if careful process parameter optimization and meticulous equipment design is done, RF heating can be successfully employed to pasteurize in-shell eggs.

Received 18 March 2013, Accepted 22 April 2013, Scheduled 27 April 2013
* Corresponding author: G. S. Vijaya Raghavan (vijaya.raghavan@mcgill.ca).

1. INTRODUCTION

Eggs are considered to be one of nature's nutritious dietary supplements. Eggs are one of the best sources of proteins, vitamins, minerals, folic acid and choline among many other micronutrients [16]. Eggs are regarded as a complete meal as it contains all the essential amino acids. Eggs are an essential ingredient in many food processing and baking industries. This is attributed to the unique functional properties of eggs such as emulsification, foaming, coagulation and browning; rendered by the proteins present in the egg [17]. Unfortunately, many recipes involve the use of uncooked raw eggs; for instance, hollandaise sauce, mayonnaise, eggnog etc.. Eggs are consumed globally and there is a constant demand for it, in the market. This calls for a safety surveillance system that establishes the microbial safety of eggs and egg products.

Due to their nutritional value, eggs are potential hosts of molds, yeasts and several bacteria notably *Salmonella enteritidis* (SE). SE is potent and efficient in successful invasion of the eggs beating innate defense mechanisms of egg. This has led to several outbreaks of Salmonellosis (more than 90%) in the recent past that were traced back to the Grade A shell eggs [20]. SE after ingestion finds its way into specialized intestinal epithelial cells where they release an enterotoxin that causes inflammation and subsequent diarrhea [14]. This might be severe which requires hospitalization in high-risk populations that includes children, elderly people and persons with compromised immune systems. As the bacteria is not able to withstand high temperature, proper cooking of the egg rules out the possibility of infection. As many recipes use raw egg, special treatment of eggs is mandatory to establish their microbial safety. The initial safety protocol insisted on the proper surveillance of SE in eggs by constantly checking the egg quality like shell integrity, washing and disinfection of the shell and environment of the egg farm. Further outbreaks due to SE in eggs have led to the consideration of alternative techniques like pasteurization of eggs. For effective pasteurization the Food Safety and Inspection Service (FSIS) of the United States Department of Agriculture (USDA) recommends heating the egg white and egg yolk to a temperature of 57.5°C and 61.1°C for 0.6 minutes respectively to render SE and other food borne pathogen in eggs inactive [10]. Egg yolk needs to be treated at a higher temperature than egg white as it has higher solid content and at the pH of the yolk (6) SE is most heat resistant [11]. Unfortunately this property of egg yolk makes it difficult to pasteurize the in-shell egg without cooking them by conventional conduction mediated heating. When the egg white and egg yolk are separated by breaking the eggs, their pasteurization becomes easier. Pasteurized egg whites could be easily found in the common market. However, repacking the egg white and yolk aseptically adds to additional processing costs. This has led to the evaluation of several methods for the pasteurization of the in-shell eggs [12].

The prescribed pasteurization temperatures for egg white and egg yolk are 57.5°C and 61.1°C as per Food Safety inspection Services of the United States Department of Agriculture (FSIS-USDA). This can be achieved by conventional conduction heating methods, i.e., water-bath heating [19]. However, the egg white gets heated up more than the egg yolk in contrary to the prescribed temperatures, as the egg yolk is concentric within the egg white. This eventually leads to the denaturation and coagulation of egg white proteins. Also the egg white gets partially cooked in the process. This affects the functional properties of the egg, thus making it undesirable for use in food processing industries. On evaluating the alternative techniques of heating for the pasteurization of eggs, the principle of dielectric heating serves as a better candidate as it employs volumetric heating principle, i.e., heats the material from within. Dielectric heating can be achieved by the application of electromagnetic radiation either in the radiofrequency or microwave frequency range.

Dielectric properties like dielectric constant and dielectric loss factor are critical parameters in designing the RF heating protocol. Dielectric constant is the permittivity of the material divided by the permittivity of the free space. It is a measure of how much the material concentrates electric flux and is equivalent electric measure of relative magnetic permeability. Dielectric loss factor is the measure of loss of power in the dielectric material which is lost in the form of heat generated due to the electric field. These dielectric properties of the material are dependent on the temperature, moisture content, and composition of the food and the frequency of the applied electric field [6]. Evaluation of the dielectric properties of the egg white and egg yolk with respect to frequency and temperature and subsequent modeling is mandatory to facilitate better designing of the pasteurization equipment. Knowledge of these properties also helps in overcoming issues like non uniformity and complexity in scaling up such equipment [7]. It has been established that the egg white has higher dielectric properties than egg yolk in microwave frequencies (200 MHz to 10 GHz). This led to faster heating of the egg white under laboratory conditions [8]. Interestingly, within the egg shell, it was found that the electric field distribution was very different leading to similar heating rates for both egg white and egg yolk. This may be attributed to the focusing effect rendered by the combination of a semi-ellipsoidal and semi-spherical architecture of the eggs. It is also important to evaluate the dielectric properties of the eggs before and after RF treatment to assess the quality of the eggs. This is essential as it has been shown that the processing of eggs might induce changes in the dielectric properties as the ingredients of the eggs changes which might directly affect the quality as well as further processing parameters [13]. In addition, a thorough understanding of the dielectric properties of the egg in radiofrequency range will enable us to design a better pasteurization procedure that will have minimal effects on the quality of the end product.

2. MATERIALS AND METHODS

2.1. Egg Samples

The fresh whole eggs within three days of grading and packing were obtained from the market (identified from the date stamped on the eggs) [4] and refrigerated at 5°C until used for a maximum of five days. They were of Canadian grade A and of small size, having an average mass of 40 g. These eggs were marketed from an egg grading station that uses chlorinated water at ambient temperature to wash the eggs before grading.

2.2. Measurement of the Dielectric Properties of Egg Components

Measurements of the dielectric properties were made with an Agilent E4991A RF Impedance/Material Analyzer (1 MHz–3 GHz) using a high temperature probe sensitive in the frequency range of 10 MHz–3 GHz. Prior to measuring the dielectric properties, the impedance analyzer was turned on and allowed to warm up for about 30 minutes. The instrument was calibrated using Agilent 16195B 7 mm Calibration kit. Eggs were cracked carefully prior to the measurements and the egg white (25 g) and egg yolk (15 g) were collected separately in small glass tubes. The probe was mounted on the stand facing downwards as shown in the schematic representation of the RF heating setup in Figure 1. The samples were heated using a heating block set at the required temperatures and placed right beneath the probe on the platform of the stand used to mount the probe. Measurements were taken at every 5°C interval from 5°C to 56°C for egg white and egg yolk. The temperatures of the sample were measured using a digital thermometer. All the measurements were made in triplicates (for the egg white and yolk at each temperature).

2.3. Evaluation of Physical Properties of Eggs after RF Heating

Most of the functional properties like whip ability, foam ability, etc., are attributes that are rendered by egg white. Effect of heat treatments on the physical properties affecting the functional quality of the egg white (recovered from the treated eggs) were measured and compared to that of fresh untreated egg white.

2.4. Heat Treatment

Heat treatment of in-shell eggs was done in triplicates (i.e.) three eggs were used for each treatment for the measurement of each parameter within the scope of this study. The treatment consisted of heating in-shell eggs in a laboratory RF heating set up working at a frequency of 27.12 MHz operating at three different heating rates 0.6, 1.26 and 2.03°C/min. The in-shell eggs were heated to a temperature of 56°C with a holding time of 0.6 minutes. The total time taken to reach this temperature was 45, 30 and 10 minutes respectively for the heating rates 0.6, 1.26 and 2.03°C/min. The temperature was measured using a fiber optic probe inserted into the egg white through the shell and the RF heating operation was controlled by the computer running HPVEE (Agilent) object oriented programming language to maintain the desired process temperature.

2.5. Measurements of the Physical Properties

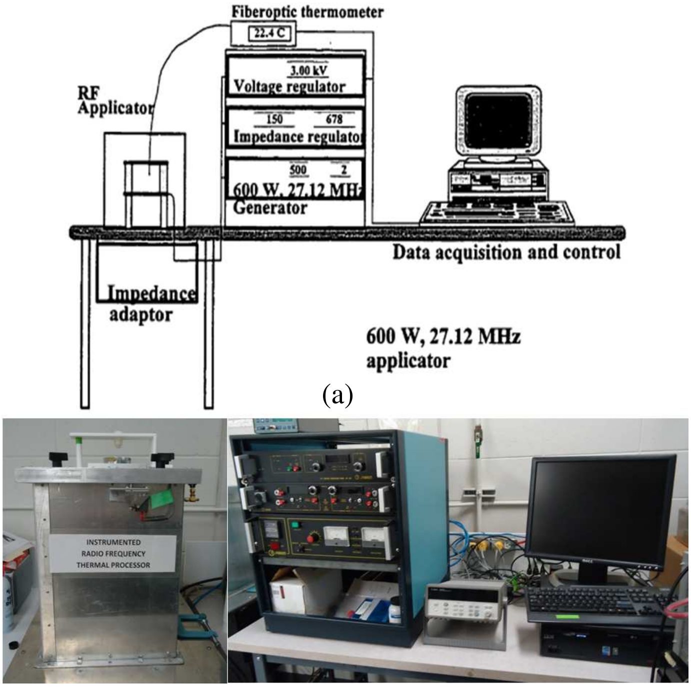
Eggs that were subjected to RF heating were cracked carefully after the heat treatment. The egg white and yolk were collected in small cylindrical beakers. The egg shell was discarded. The egg white was then used for evaluating the physical properties.

2.6. Viscosity

To evaluate the viscosity of the heat treated and untreated egg white and yolk sample, Brook field viscometer and a temperature controlled water bath were used. Measurements were made for each sample treated at different heating rates in triplicates. The measured viscosity values were compared with the values of the untreated white and yolk samples.

2.7. Foam Density and Foam Stability

Foam density is a measure of thickness of the foam. The foam thickness indicates the amount of the air that is trapped in the foam. The



(b)

Figure 1. RF heating setup. (a) Schematic and (b) Pictorial representation of the RF heating setup.

functional quality of the egg is determined by the foam stability. The egg white samples were foamed using Braun 60 Egg Beater (USA) in a 500 ml cylindrical beaker. The foaming process consisted of beating 40 ml of egg white for 2 minutes at a speed of 2000 rpm. The mass of the foam is calculated using a weighing balance. Then the density of the foam is calculated using the Equation (1).

$$\text{Foam density} = \frac{\text{mass of the foam}}{\text{volume of the foam}} \tag{1}$$

To determine the foam stability, an experimental set up devised by Dev et al. 2008 was used. The quantity of liquid drained as a function of time from the completion of foaming was taken as an indicator of the foam stability. Foam stability measurements were taken for 180 minutes after foaming.

2.8. Turbidity

Turbidity is a direct measure of the extent of protein coagulation [21]. The amount of light absorbed (absorbance) is a function of the turbidity of a liquid. As proteins coagulate, the transmittance of light through the egg white reduces. The absorbance of the heat treated and untreated egg white samples was measured at 650 nm using a Biochrom Ultra spec 2100 Pro spectrophotometer at 24°C. Plain demineralized water was used for calibration. An absorbance value of 0% corresponded to zero turbid solution.

2.9. Hyperspectral Imaging

The hyperspectral imaging system used for the study consisted of 2 line-scan spectrographs, namely ImSpector (ImSpector, V10E, Spectral Imaging Ltd., Finland) with a spectral range of 400 to 1000 nm and HyperspecTM (Headwall Photonics Inc. USA) with a spectral range of 900 to 1700 nm. Transmittance characteristics in the spectral range of 400 to 1700 nm for radiofrequency heated eggs. An unsupervised k-means classification was performed to classify the spectral data within a 95% confidence interval. The hypothesis behind this investigation was that the presence of any heat damage to proteins inside the shell egg can be quantified in terms of variation in transmittance.

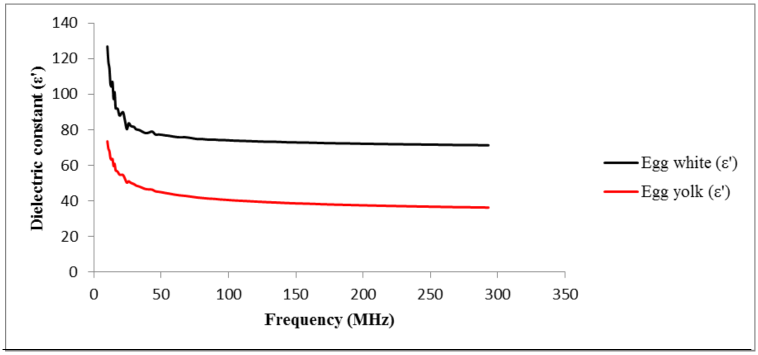
2.10. Data Analysis

CurveExpert Basic 1.4 Software was used to analyze the collected data and to establish the mathematical relationships for the dielectric constant and loss factor as a function of frequency and temperature. MATLAB Version R2010a (MathworksInc., USA) was used to preform multiple linear regression analysis of the hypercubes (resulting from the hyperspectral imaging) to identify the informative wavelengths. An unsupervised k-means classification of the spectral data was performed using the ENVI version 4.7 software (ITT Visual Information Solutions, CO, USA).

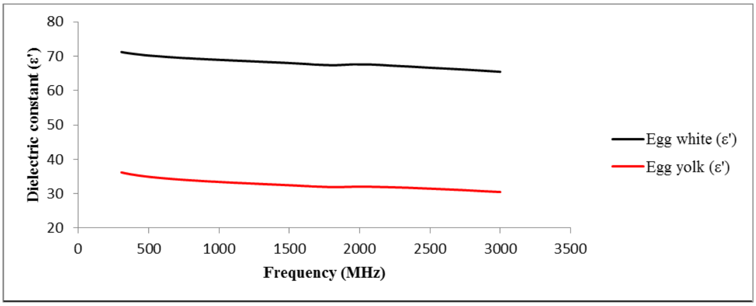
3. RESULTS

3.1. Dielectric Properties of the Egg Components

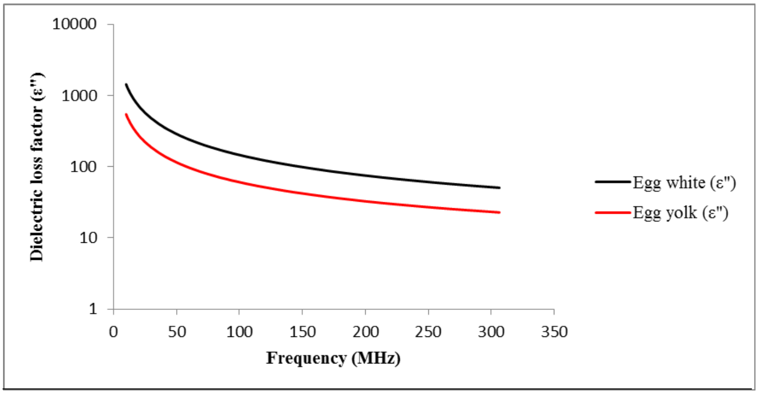
As shown in the Figures 2(a) and 2(d), the dielectric constant and loss factor of the egg white and egg yolk has distinct behavior in the radio frequency range (10 MHz–300 MHz) at 25°C compared to that the microwave frequency range (300 MHz–3000 MHz) at 25°C. The net effect on the dielectric constant and loss factor due to frequency changes is that both the parameters decreased with increase



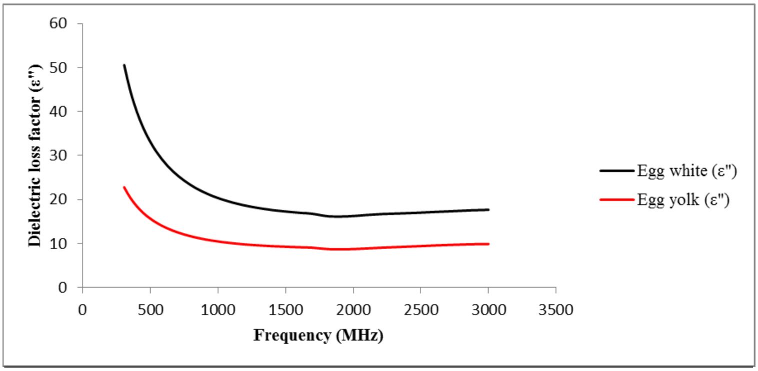
(a)



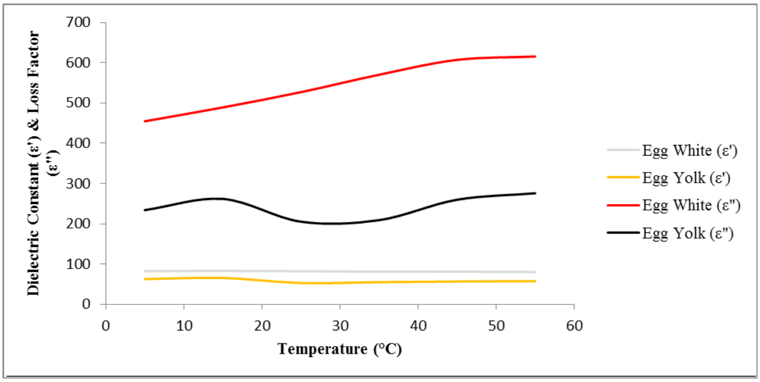
(b)



(c)



(d)



(e)

Figure 2. (a) Change in the dielectric constant of egg components with varying frequencies (10–300 MHz). (b) Change in the dielectric constant of egg components with varying frequencies (300–3000 MHz). (c) Change in the dielectric loss factor of egg components with varying frequencies (10–300 MHz). (d) Change in the dielectric loss factor of egg components with varying frequencies (300–3000 MHz). (e) Change in dielectric properties of egg components with varying temperatures at 27.12 MHz.

in frequency (Figures 2(a)–(d)). In the radio frequency range, initially the dielectric constant has a higher slope as the frequency increases from 0 Hz up to 50 MHz and then the slope decreases above frequency of 50 MHz (Figures 2(a) & (b)). Dielectric constant for egg white and yolk appeared linearly related to frequency in a similar fashion as that of water and also the dielectric properties of the egg white appeared to be much closer to that of water [5]. At any given temperature and frequency, repeatability of the measurements was excellent and the variances calculated among replicates were smaller than 0.18. The decrease in the dielectric constant and the loss factor can be explained upon consideration of the polarization mechanisms in detail. This trend can be explained based on the phenomenon of dielectric relaxation which is the lag in the dielectric constant of the material in response to an external field. Here the dipoles are unable to keep up with the alternating electric field. The time delay between the electric field and dipole polarization suggests a permanent degradation of free energy. In accordance with the Debye model this frequency is dependent on the viscosity of the liquids, such that more viscous liquids relax at lower frequencies as compared to the less viscous ones [2]. In eggs, the suspended matter is biomolecules and electrolytes and has much lesser relaxation frequencies than water. Since the net dielectric constant decreases with increasing frequency, the total charge stored decreases and as a result the dielectric loss factor also decreases with increasing frequency.

It is evident that the egg white possesses higher dielectric constant than the yolk which can be attributed to the high water content of the egg white ($\approx 90\%$) than egg yolk ($\approx 50\%$) and it closely resembles that of water. Since the water content is high, there is high rotational polarization in the egg white than the egg yolk; as a result the net dielectric constant is higher.

As shown in the Figure 2(e), the dielectric constant of the egg white and the egg yolk slightly decreased with increasing temperature at 27.12 MHz. This is due to the loss in their rational polarization as the molecules deviate from aligning to the alternating electric field due to high thermal energy readily available. This thermal energy facilitates random motion of the molecules. Therefore, the molecule deviates from properly aligning to the alternating electric field, The dielectric loss factor of the egg white increases with increasing temperature, which may be due to the increase in the ionic polarization due to increase in the number of free ions available. This can be duly confirmed by measuring the ionic conductance of the egg white at different temperatures. However, the dielectric loss factor of the egg yolk follows a random pattern. The loss factor initially decreases and then increases. The initial decrease may be due to the massive decrease in their polarization by re-orientation. At high temperatures, due to high solid content in the yolk, the thermal energy may render several ions free, which may contribute to the increased loss of energy. Ionic conductance has been proven to play a major role at RF while water molecules affect dielectric properties at higher frequencies [23]. Determining their ionic conductance may help in proving the above hypothesis.

The following Equations (2)–(5) are derived for the dielectric properties as a function of the temperature and frequency by fitting the data using Curve Expert (Version 1.4). These equations can help determine the dielectric constant and dielectric loss factor for any given temperature and frequency within the scope of this study, i.e., in the frequency range of 10 MHz to 3 GHz and in the temperature range 5°C to 56°C.

$$\varepsilon'(EW) = \left(71.2 - 0.12T + 0.0004T^2\right) e^{\frac{(4.84+0.03T)}{f}} \quad R^2 = 0.98 \quad (2)$$

$$\varepsilon'(EY) = \left(21.53 + 6.36T - 0.0435T^2 + 0.010T^3 - 0.00008T^4\right) e^{\frac{\left(13.73-1.40T+0.086T^2-0.0019T^3+0.00001T^4\right)}{f}} \quad R^2 = 0.97 \quad (3)$$

$$\varepsilon''(EW) = 6.18 - 0.00026T - 0.00024T^2 + \frac{\left(12349.8 + 60.5T + 0.54T^2\right)}{f} \quad R^2 = 0.98 \quad (4)$$

$$\varepsilon''(EY) = 10.57 + 8.30T - 0.535T^2 + 0.012T^3 - 0.00095T^4 + \frac{\begin{pmatrix} 12.83 - 1.28T + 0.07T^2 \\ - 0.0018T^3 + 0.000013T^4 \end{pmatrix}}{f} \quad R^2 = 0.95 \quad (5)$$

where, EW — Egg White, EY — Egg Yolk, f — Frequency (MHz) and T — Temperature (°C).

4. STUDY ON THE PHYSICAL PROPERTIES OF THE EGG

4.1. Viscosity

Viscosity of the egg white is one of the important characteristics that determine most functional properties like emulsification, whip ability and gelling properties of the egg [15]. Any adverse effects on the viscosity of egg white will directly affect these properties and would make egg unsuitable for food industrial use. Also, reduction in viscosity has shown to have adverse effects on the shelf life of the eggs [3]. Therefore, it is important to design an RF heating process with minimal/no impact on the viscosity. The viscosity of egg white and yolk measured after breaking open the heat treated eggs and the untreated eggs are shown in the Figure 3. As expected the viscosity of the egg white of the untreated egg is lesser than that of the egg yolk. This is because egg yolk has 50% solid matter which includes fatty acids that adds up to the viscous nature of the yolk. The viscosity of the egg white and egg yolk of the heat treated eggs decrease with increasing heating rates, i.e., 0.6 > 1.26 > 2.03°C/min. This can be correlated to the denaturation level of the protein. If the denaturation is high, then the viscosity decreases drastically. Viscosity is a critical parameter in determining the emulsifying properties of the egg white. The viscosity of egg white treated at 0.6°C/min is close to that on the untreated eggs which in turn shows that there is minimum protein coagulation at 0.6°C/min, whereas at 2.03°C/min, the decrease in viscosity is significantly higher (one-third of the untreated eggs) that can be attributed to the increased coagulation of the protein.

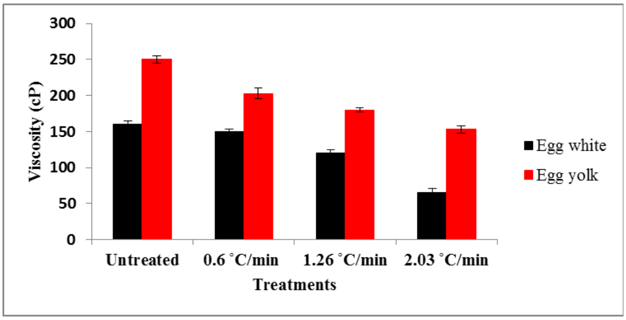
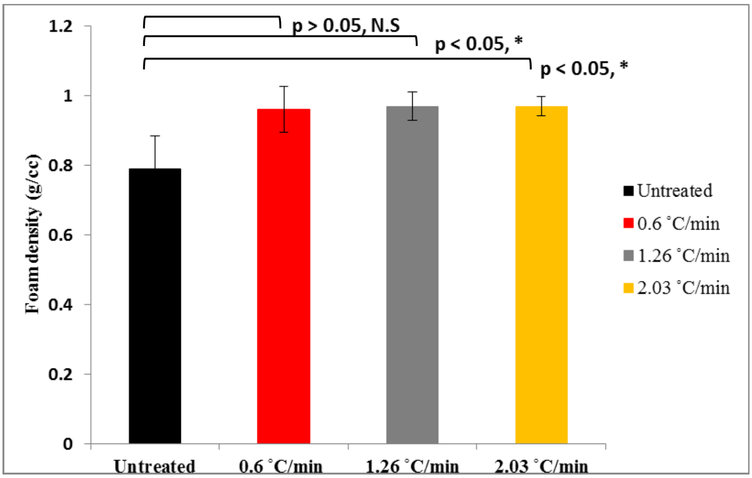


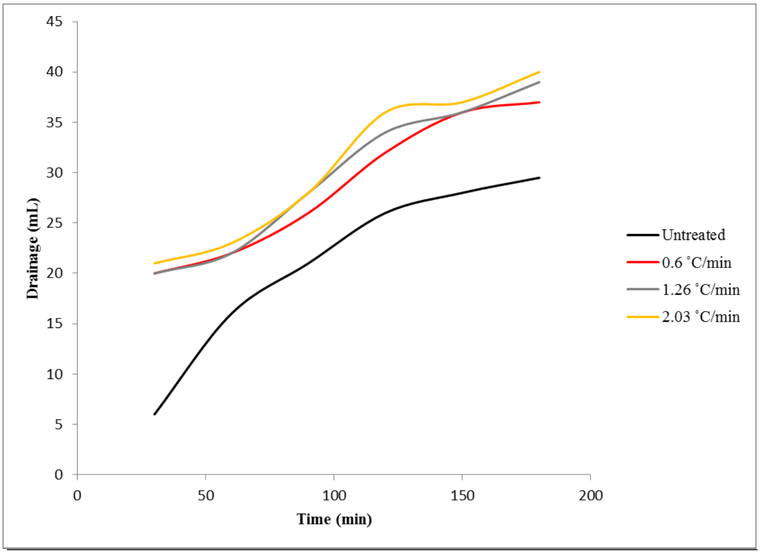
Figure 3. Viscosity profiles of the eggs after RF heating at different heating rate (°C/min).

4.2. Foam Density and Foam Stability

Foam in general is a two phase system. While mechanical whipping of egg white, air gets trapped between the egg white proteins that are denaturing. The trapped air contributes to the dispersed system and the denatured proteins forms a thin layer thereby contributing the surface phase [1]. Foam ability of the egg is an essential attribute of the egg white which makes it indispensable in food applications especially in confectionary. This makes it essential to evaluate the effects of RF heating on this attribute of egg white to determine the quality of the egg. Foaming ability of the egg is very important in food processing and baking industrial application. Better foaming ability is associated with lower foam density. The foam density data obtained at different heating rates of heat treatment is shown in the Figure 4(a). The data clearly shows that the density has increased after the heat treatment. Interestingly, the varying heating rates seem to have no effect on the foaming ability. Foaming stability is indicated by the amount of liquid drained with time. The foam stability profile is shown in Figure 4(b). The foam stability decreases significantly ($p < 0.05$) between the untreated and RF heated egg white. As the heating rate increases from 0.6 to 2.03°C/min, the foam stability decreases. To sum up, foam stability is quite sensitive to thermal treatment. The more



(a)



(b)

Figure 4. (a) Foam density of the eggs after RF heating at different heating rates (°C/min). (b) Foam stability profiles of the eggs after RF heating at different heating rates (°C/min).

the heating rate the less is the foam stability. It should be noted that while designing an RF heater a balance should be achieved where an optimal heating rate with minimal effects on the foam stability.

4.3. Turbidity

Egg white is rich in proteins. In general egg white is less turbid and transmits light. As it is heated, the proteins in the egg white denature and the egg white becomes increasingly turbid. As a result transmittance of the more denatured egg white decreases. Therefore, turbidity would be a direct measure of the denaturation status of the proteins in the egg white. This would in turn dictate the quality of the egg white and in turn the functional properties. Turbidity analysis on the egg whites of the treated eggs revealed that there was significant protein coagulation occurring at all the heating rates of heat treatment (0.6, 1.26 and 2.03°C/min). The turbidity values increased with increasing heating rates ($0.6 < 1.26 < 2.03$°C/min) (Figure 5). In other words, protein coagulation increased with increased heating rates. Though the heating time decreased with increasing field strength, protein coagulation level is still of major concern. The functional properties of the eggs directly depend on the proteins that are in proper structural orientation and stability. Therefore, an optimized method of heating the eggs to the required temperature without compromising the protein quality is essential for industrialization of the process.

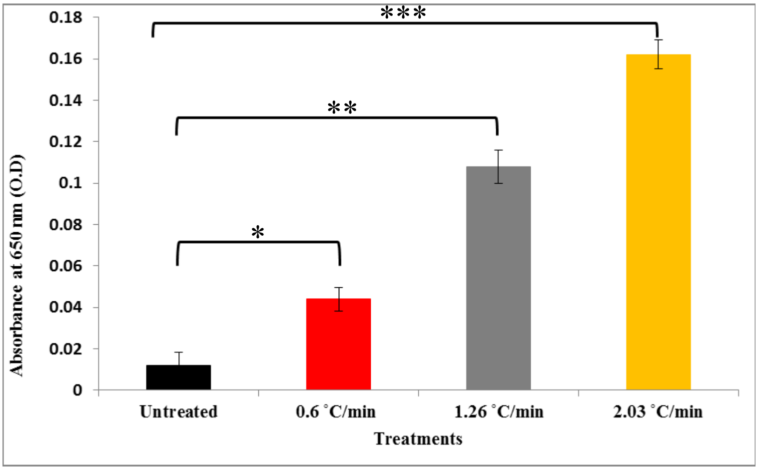


Figure 5. Turbidity profiles of the eggs after RF heating at different heating rates (°C/min).

4.4. Hyperspectral Study

Non-invasive quality assessment tools are being hunted by food industries as they ensure hygiene of the product by avoiding risk of any unintended contamination at the same time providing reliable quality assessment. One such technique is spectroscopy, which is fast, non-contact and non-invasive making it an ideal candidate to evaluate the quality of eggs after RF treatment. This type of quality assessment is advantageous in that large number of eggs can be graded at less time. Visible/ Near Infrared spectroscopy is gaining attention for quality assessment of food produce especially fruits and vegetables. This technology has also been evaluated for the prediction of shell pigmentation, freshness, blood and meat spots, and hatching eggs [18, 24]. The feasibility of using visible transmission spectroscopy as a non-destructive method to assess the freshness of an egg was investigated by Kemps et al.. The spectral data of 600 white-shelled eggs were compared with the pH and the HU (Haugh unit, a unit for describing egg freshness, based on the thickness of the albumen) showed that the light transmission spectrum of an egg can provide quantitative information about egg freshness.

The two spectral data hypercubes obtained from the two cameras were merged using MATLAB R2010a and multiple linear regression analysis was done for subset selection [22]. From 2151 wavebands scanned, 10 wavelengths (5 from the visible spectral range and 5 from the NIR range as shown in the Table 1) were chosen as informative wavelengths as they have an $R^2 > 0.90$ in the multiple linear regression

Table 1. Informative wavelengths for hyperspectral classification of egg quality.

S. No	Wavelength (nm)	R^2
1	411	0.96
2	444	0.93
3	484	0.91
4	530	0.96
5	661	0.97
6	936	0.93
7	1196	0.96
8	1345	0.92
9	1402	0.96
10	1719	0.97

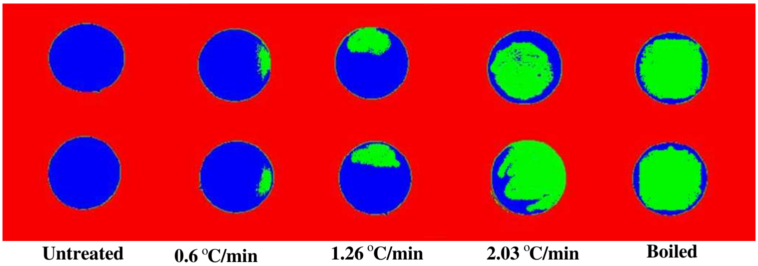


Figure 6. Unsupervised k-means classified hyperspectral image for the informative wavelengths.

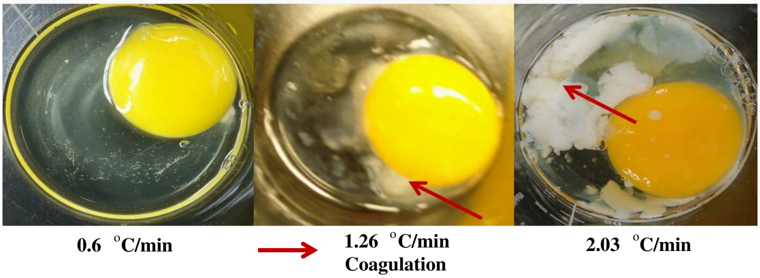


Figure 7. Coagulation profiles of the RF heated eggs at different heating rates (°C/min).

analysis for maximum R^2.

Figure 6 shows an unsupervised k-means classified mosaic made from two eggs from each treatment. It is clear that as the heating rate increases, the quality of the egg decreases. From the Figure 6 it is clear that the eggs heated at 2.03°C/min have more pronounced coagulation than lower heating rates. At 0.6°C/min, the quality of eggs was close to that of the untreated eggs. Eggs treated at 1.26°C/min had moderate coagulation in the egg. The Figure 7 shows the coagulated profile of eggs after breaking open the heat treated eggs. While comparing the Figures 6 and 7 it is clear that the results of the hyperspectral data are in accordance with the observed results.

4.5. Discussion

Eggs are one of the complete protein rich foods that are known to us. Since most of our recipes and diverse food processing application employ raw eggs, it is essential to ensure that they are safe. Because of their rich nutrient potency, they serve as good culture medium for microbes. In order to ensure their safety, several methods are under analysis for large scale applicability. Recently, dielectric heating is under the radar for pasteurizing in shell eggs as they employ volumetric heating principle. This is nothing but to heat a substance from within rather than like traditional convective or conduction mediated heating. This is highly advantageous particularly in case of eggs, as the egg white and egg yolk have distinct thermal properties. Egg yolk needs to be heated to higher temperature than egg white to achieve pasteurization. This is not possible in traditional heating methods as the egg white would be partially or completely cooked before attaining such temperatures which is undesirable. But in volumetric heating this differential heating is achievable with careful process design. This study is aimed at providing basic knowledge on the dielectric properties of the egg white and egg yolk in the radio frequency (10 MHz–300 MHz). Also, the quality of the egg white is assessed after heat treatment to evaluate the efficacy of the process.

The Figures 2(a) to 2(e) give the general trend of the dielectric properties in the radio frequency range and at different temperatures. Having this knowledge is crucial for a proper process design which would aid in differential heating with minimal damage to the different proteins in the egg white. In general, dielectric properties of the egg white are better than the egg yolk which might be attributed to their higher water content. The trend for the dielectric loss factor observed in the radio frequency for egg yolk is very encouraging. With careful process design egg yolk could be heated to pasteurization temperatures with minimal or no damage to the egg white. Simulation studies conducted with several process considerations shows that a practical process where the eggs are rotated in specially designed RF applicator would render the required selective heating [9]. The quality assessment of the eggs is essential and is a direct measure of the efficiency of the RF heating process. In this study the parameter tested are viscosity, foam density, foam stability and turbidity which are all direct measure of the damages caused to the proteins in the egg white. The viscosity of the egg white and egg yolk of the heat treated eggs decrease with increasing heating rates, i.e., $0.6 > 1.26 > 2.03°\mathrm{C/min}$ (Figure 3). The foam density decreased after the heat treatment irrespective of varying heating rates (Figure 4(a)). On the other hand foam stability decreased with increasing heating rates (Figure 4(b)). Turbidity increased with increasing heating rates indicating that there is more protein denaturation at higher heating rates (Figure 5). From these analyses it is quite clear that lower heating rate least affects the quality of the egg white. This is clearly evident in the hyperspectral analyses conducted, the egg treated at the lower heating rate matched closely to the untreated and the egg processed at higher heating rate matched closely to the boiled egg. So this shows that upon meticulous process design the harmful effects on the egg quality could be avoided at the same time achieving differential heating of egg yolk required to pasteurize in shell eggs.

5. CONCLUSION

The study of dielectric properties is important to under the behavior of the components of egg when heated using radiofrequency. This is a dire necessity for an effective process design. The overall dielectric behavior of the major egg components (egg white and yolk) were found suitable to be manipulated in an effective way to design an efficient RF heating process with minimal damage to the functional attributes of the egg. Egg white owing to its increased water content resembled close to the dielectric profile of water. The egg-shell and shell membrane showed very good transparency to radio waves in their dielectric properties, thereby making inshell egg pasteurization by radiofrequency heating possible with a careful RF design.

A qualitative analysis on the egg components after RF heating showed that with increase in the heating rate viscosity and foam stability decreased while turbidity and coagulation increases as determined from spectrometric and hyperspectral studies. This calls for careful process design wherein equilibrium between minimal adverse effects on the different functional properties as well as required temperature for effective heating of the in-shell egg to the desired temperatures could be achieved for effective RF heating and hence making eggs safer for our consumption.

ACKNOWLEDGMENT

The authors are sincerely thankful for the financial support by the Canadian International Development Agency (CIDA) and Natural Sciences and Engineering Research Council (NSERC) of Canada for the study.

REFERENCES

1. Acker, L. and W. Ternes, "Chemische zusammensetzung des eies," *Ei und Eiprodukte*, 90–196, W. Ternes, L. Acker, and S. Scholtyssek, Editors, Verlag Paul Parey, Berlin und Hamburg, 1994.

2. Bircan, C. and S. A. Barringer, "Use of dielectric properties to detect egg protein denaturation," *Journal of Microwave and Electromagnetic Energy*, Vol. 37, No. 2, 89–96, 2002.
3. Caner, C. and O. Cansiz, "Chitosan coating minimises eggshell breakage and improves egg quality," *Journal of the Science of Food and Agriculture*, Vol. 8, 56–61, 2008.
4. CEMA, *The Canadian Egg Industry Fact Sheet: Canadian Egg Marketing Agency*, 2004.
5. Collie, C. H., J. B. Hasted, and D. M. Ritson, "The dielectric properties of water and heavy water," *Proceedings of the Physical Society*, Vol. 60, No. 2, 145, 1948.
6. Datta, A., G. Sumnu, and G. S. V. Raghavan, *Dielectric Properties of Foods. Engineering Properties of Foods*, M. A. Rao and A. Datta, Editors, Taylor & Francis Publications, Boca Raton, Florida, 2005.
7. Debard, C., "Innovating and efficient dielectric heating applications in the industry: Some case studies," *Proc. Fourth World Congress on Microwave and Radio Frequency Applications*, Austin, Texas, Nov. 2004.
8. Dev, S. R. S., G. S. V. Raghavan, and Y. Gariepy, "Dielectric properties of egg components and microwave heating for in-shell pasteurization of eggs," *Journal of Food Engineering*, Vol. 86, 207–214, 2008.
9. Dev, S. R. S., S. Kannan, Y. Gariepy, and G. S. V. Raghavan, "Optimization of radio frequency heating of in-shell eggs through finite element modeling and experimental trials," *Progress In Electromagnetics Research B*, Vol. 45, 203–222, 2012.
10. FSIS-USDA, *Risk Assessments for Salmonella Enteritidis in Shell Eggs and Salmonella Spp. in Egg Products*, FSIS, Omaha, NE, 2006.
11. Garibaldi, J. A., R. P. Straka, and K. Ijich, "Heat resistance of salmonella in various egg products," *Appl Microbiol.*, Vol. 17, No. 4, 491–496, 1969.
12. Hou, H., R. K. Singh, P. M. Muriana, and W. J. Stadelman, "Pasteurization of intact shell eggs," *Food Microbiology*, Vol. 13, 93–101, 1996.
13. Jain, R. C. and W. A. G. Voss, "Dielectric properties of raw and cooked chicken egg at 3 GHz, 23–40°C," *The Journal of Microwave Power and Electromagnetic Energy*, Vol. 22, 221–227, 1987.
14. Jones, B. D., N. Ghori, and S. Falkow, "Salmonella typhimurium initiates murine infection by penetrating and destroying the

specialized epithelial M cells of the Peyer's patches," *J. Exp. Med.*, Vol. 180, 15–23, 1994.

15. Kemps, B. J., F. R. Bamelis, K. Mertens, E. M. Decuypere, J. G. De Baerdemaeker, and B. De Ketelaere, "The assessment of viscosity measurements on the albumen of consumption eggs as an indicator for freshness," *Poultry Science*, Vol. 89, 2699–2703, 2010.
16. Li-Chan, E. C. Y., W. D. Powrie, and S. Nakai, *The Chemistry of Eggs and Egg Products. Egg Science and Technology*, W. J. Stadelman and O. J. Cotterill, Editors, Food Products Press, New York, 1995.
17. McDonnell, L. R., R. E. Feeney, H. L. Hanson, A. Campbell, and T. F. Sugihara, "The functional properties of the egg white proteins," *Food Technology*, Vol. 9, 49–53, 1955.
18. Narushin, V. G., T. A. Van Kempen, M. J. Wineland, and V. L. Christensen, "Comparing infrared spectroscopy and egg size measurements for predicting eggshell quality," *Journal of Biosystems Engineering*, Vol. 87, 367–373, 2004.
19. Schuman, J. D., B. W. Sheldon, J. M. Vandepopuliere, and H. R. Ball, Jr., "Immersion heat treatments for inactivation of Salmonella enteritidis with intact eggs," *Journal of Applied Microbiology*, Vol. 83, 438–444, 1997.
20. St. Louis, M. E., D. L. Morse, and M. E. Potter, "The emergence of grade a eggs as a major source of salmonella enteritidis infections: New implications for the control of salmonellosis," *Journal of American Medical Association*, Vol. 259, 2103–2107, 1988.
21. Van der Plancken, I., A. V. Loey, and M. E. Hendrickx, "Effect of heat-treatment on the physico-chemical properties of egg white proteins: A kinetic study," *Journal of Food Engineering*, Vol. 75, No. 3, 316–326, 2006.
22. Ventura, M., A. De Jager, H. De putter, and F. P. M. M. Roelofs, "Non-destructive determination of soluble solids in apple fruit by near infrared spectroscopy," *Postharvest Biology and Technology*, Vol. 14, No. 1, 21–28, 1998.
23. Wang, J., J. Tang, Y. Wang, and B. Swanson, "Dielectric properties of egg whites and whole eggs as influenced by thermal treatments," *Food Science and Technology*, Vol. 42, 1204–1212, 2009.
24. Wei, R. and J. J. Bitgood, "A new objective measurement of eggshell color. 1. A test for potential usefulness of two color measuring devices," *Poultry Science*, Vol. 69, 1175–1780, 1989.