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Novel Technique for Measurements of Dielectric Properties and Microwave Heating of In-Shell Eggs without Explosions in Microwave Oven for Pasteurization

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Abstract— Shell eggs are splattered out when they are subjected to microwave heating. In this paper, microwave heating of in-shell eggs without explosions in a domestic microwave oven has been done by identifying suitable power regions. First objective of this study was to measure dielectric properties of egg components which are so important in microwave heating. Second objective was to model and analyze electromagnetic power distribution inside a microwave oven working at 2450 MHz with in-shell egg as load. The study revealed that the albumen has higher dielectric properties than the yolk which is leading to its faster heating rate and cause to splatter at high energy points. The spots where the albumin got less cooked comparatively are marked as low power regions. It becomes evident when a whole shell egg placed at the identified low power regions in real microwave oven it was found well cooked without explosion.

Keywords— Microwave heating; Shell eggs, Electromagnetic power distribution, Dielectric properties

1.INTRODUCTION

Egg is an excellent food supplement, giving almost every essential amino acid which most of our regular diet may lack. It is also an excellent source of vitamin A, B3 and Folate. It also contains useful amounts of many other vitamins and minerals. Egg is used as a vital ingredient in several foods and food industries, especially for their exceptional functional properties. Eggs are one among the major animal foods mostly marketed raw and frequently consumed in various cooked forms.

The Food Safety and Inspection Service (FSIS) of United States Department of Agriculture (USDA) suggests heating the egg white and the egg yolk to 57.5°C and 61.1°C, respectively, for 2 minutes to ensure egg safety against Salmonella and other food borne pathogens (FSIS-USDA, 2006). This is possible by conventional heating methods only if the yolk and egg white are separated before processing. But breaking and repacking them aseptically involves huge additional costs. Therefore in-shell pasteurization has gained great commercial importance in recent times.

The current technique for in-shell pasteurization of egg involves heating the eggs in a water bath at 60°C for about 20–25 min, depending on the size of the eggs. This leads to the overheating of the egg white proteins (i.e., the egg white gets heated up more than the yolk, which is against the recommendations) resulting in denaturizing and coagulation . This denaturizing greatly affects the functional properties of the eggs Therefore a process that can heat the shell eggs from inside will be a better alternative to solve this problem. Microwave heating exploits the dielectric behavior of the substance exposed to it to generate heat from within the substance (Kai Knoerzer et al, Metaxas, A et al). But this direct heat generation occurs only up to a certain depth of the product from the surface. This is due to the fact that depending on the dielectric properties of the substance, there is an exponential decay of microwave energy as the waves penetrate into the product from the surface.

The Dielectric properties of the food are physical values that determine the heat generation when food is irradiated by the Microwaves and change in response to the ingredients and temperature of the food. Theoretical and mathematical studies have shown that even though albumen exhibits better dielectric properties than yolk, the egg's curvature has a focusing effect which leads to a suitable power distribution. The shell egg appears ideally suited for pasteurization and cooking in a microwave environment.

Modeling changes in dielectric properties of the albumen and yolk with temperature and frequency will allow predicting the same at any prescribed temperature and frequency thereby facilitating equipment design and process optimization to ensure best end product quality. A complete understanding of the dielectric properties and egg curvature on power distribution will help design a system highly specific and efficient for this application (S.R.S. Dev et al). The egg-shell as nature's oldest container proved to be a reliable construction for protecting life. In many of the applications shell-like constructions operate under an internal pressure and they usually fail due to an excess internal load which can arise either as a result of slowly driving the system above its stability limit, or by a pressure pulse caused by an explosive shock inside the shell (F. Wittel et al).Manufacturers of microwave ovens recommend that items such as eggs or packaged products be pierced several times before heating. This is because microwaves are able to create high levels of pressure inside sealed objects, which if high enough will cause an explosion. Injuries from exploding microwave-heated eggs may include facial or ocular burns and even ocular penetration. Even eggs removed from their shells may explode (Tzu-Ching Shih et al). The force generated by an exploding egg is great enough to blow open the door of a microwave oven and hence more should be done to educate people not to cook eggs in microwave ovens (Andrew Tatham et al, Jian Wang et al).

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Therefore this study was conducted with the following objectives: (i) To measure dielectric properties of various components of Egg like white Albumen, Yellow yolk, Egg shells and thin membrane (ii) To identify locations in a domestic microwave oven to heat the shell egg without explosions at a frequency of 2.45 gigahertz (GHz) (iii) To corroborate the theoretical results with experimental setup.

2. Materials and Methods

The fresh whole eggs, within three days after packing (identified from the best before date stamped on the eggs by supplier), used in this study were procured from the local market and kept in a refrigerator until used. They were all of normal size with an average weight of 60 g each. These eggs were marketed from an egg grading company that uses chlorinated water at ambient temperature to wash the eggs before grading (Metaxas, A et al).

A common misconception is that microwave ovens cook food "from the inside out". In reality, microwaves are absorbed in the outer layers of food in a manner somewhat similar to heat from other methods. The misconception arises because microwaves penetrate dry non-conductive substances at the surfaces of many common foods, and thus often induce initial heat more deeply than other methods. Depending on water content, the depth of initial heat deposition may be several centimeters or more with microwave ovens, in contrast to broiling (infrared) or convection heating, which deposit heat thinly at the food surface. Penetration depth of microwaves is dependent on food composition and the frequency. Lower microwave frequencies (longer wavelengths) are penetrating better (M.E.C. Oliveira et al, Barbosa-Cánovas G.V et al).

Dielectric properties are also important in the selection of proper packaging materials and cooking utensils and in the design of microwave heating equipment, because they describe how the material interacts with electromagnetic radiation (Jian Wang et al). Studies of heating uniformity and temperature elevation rate involve dielectric properties (L. Ragni et al, Luigi et al). Typical features of power density patterns of a load are large internal hot and cold areas, internal focusing effects, and the edge-heating phenomenon. For example, when a raw egg is heated it may explode because the power density near its center is much higher than in other parts, causing violent devastating as the interior becomes superheated.

The dielectric properties of materials are very important in evaluating the penetration depth of energy i.e. the distance at which the power drops 37 % of its value in the material. In this study, dielectric properties (dielectric constant and dielectric loss factor) of in-shell eggs were studied by using solid dielectric cell. In real life heating devices the greater uniformity of power distribution inside the heated objects is often achieved with the object movement inside the cavity while heating is on. In industrial ovens the foodstuffs are simply passing through a cavity on a conveyor belt while in small-scale simpler devices like domestic microwave oven the object is placed on a rotating shelf (Paweł Kopyt et al) which is called as turn table. Power distribution inside a domestic microwave oven at a frequency of 2.45 Gigahertz was investigated by MATLAB. Power distribution inside a domestic microwave oven at the said frequency was investigated by avoiding carousel (turn table). The carousel is one of the earliest and the most intuitive methods of increasing temperature uniformity inside a microwave oven. Microwave ovens heat food volumetrically by electromagnetic radiation (S.S.R. Geedipalli et al, Suvi Ryynänen et al). The carousel helps in increasing the temperature uniformity of the food by about 40%. Power distributed inside a microwave oven without turntable is not uniform. This non uniformity of power distribution has been conceptualized to cook egg by identifying low temperature regions over entire volume of the oven (Satish kumar, R et al).

2.1. Measurement of Dielectric properties of Egg components

Dielectric parameters of egg constituents have been measured by using SICO Solid Dielectric cell with the setup shown in Figure1.Eggs (laid not before three days) marketed by egg grading company were bought and carefully cracked to separate the constituents like albumen, yolk, shells and membranes.

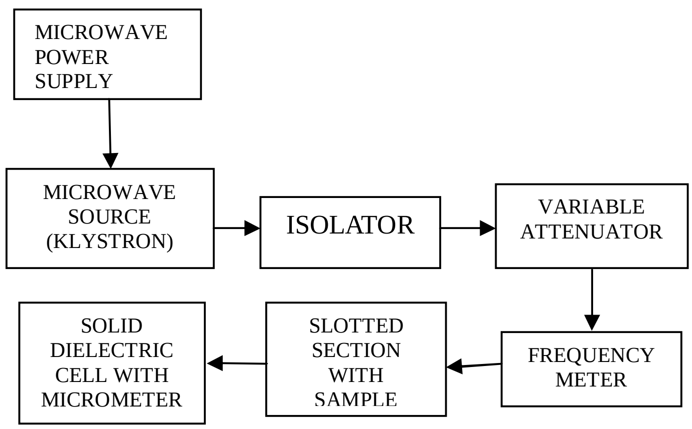

Figure 1 Block diagram for Dielectric Measurement

A container made up of materials not conduct electricity is prepared to fit the dielectric cell. Egg white and yolk can be filled in the container and will have inner dimensions of the container as they are liquids with different density as shown in Figure 2. Shells and membranes were cleaned and dried well to pack them in the container for the measurement.

Figure 2 Separated Egg constituents (samples)

Power supply, Klystron, Isolator, Variable Attenuator, Frequency meter, Slotted section with the collected sample and Solid Dielectric cell are connected as shown in Figure 3 and experiment has been done with the following procedure from steps 1 to 11.

1. Energise the microwave power source and obtain suitable power level in the indicating meter when empty sample has been placed inside slotted section .
2. Read and record the position of standing wave voltage minima and determine λg by double minima method.
3. Measure frequency of the wave by frequency meter.
4. With probe positioned at the maximum of the standing wave pattern, fill the cell with the sample under test, taking out the shorting plunger. Install the plunger in the cell & move it through the dielectric till it touches the 90° bend of dielectric cell.
5. Slowly move the plunger up and record the minima.
6. Move the plunger down till meter reads double of that in step 5 &record the plunger position, say X1.
7. Move the plunger up till meter reads double the value at the minima in step 6 & record the plunger position say X2.
8. Find the double minima width (X2 - X1) $=\Delta X$
9. Move the plunger up when it is positioned on the second minimum measure and record the position of the minimum & double the minimum width.
10. Record VSWR meter reading.
11. Repeat the procedure for various samples collected at different temperatures.

Figure 3 Experimental setup for measuring dielectric properties.

2.2. Computation of dielectric properties

2.2.1 Readings recorded at room temperature

Beam voltage has been set at 270 V

Repeller voltage has been set at -228 V

First minima for empty waveguide	: 9.3 cm
Second minima for empty waveguide	: 12.3 cm
First minima for albumen sample	: 9.1 cm
Second minima for albumen sample	: 11.65cm
First maxima for albumen sample	: 9.8 cm
VSWR for albumen sample	: 2.6
First minima for yolk sample	: 8.8 cm

Second minima for yolk sample : 11.4 cm
First maxima for yolk sample : 9.75 cm
VSWR for yolk sample : 3.9

2.2.2 Formulae used

Propagation constant $k = \frac{2\pi}{\lambda_g}$ (1)

Where, λ_g is guide wave length

$$C\angle\phi = \frac{\tan X}{X}$$

Where $X = T\angle T$ and

$$\phi = 2k(D - D_R - l_\epsilon)$$

D_R is a minima of empty wave guide
D is a new minima with sample

$AdmittanceY_\epsilon = \left(\frac{T}{Kl_\epsilon}\right)^2 \angle 2(T - 90^\circ)$ (2)

Where l_ϵ sample length

$$Y_\epsilon = G_\epsilon + jB_\epsilon$$

Here G_ϵ and jB_ϵ are real and imaginary part of Y_ϵ

Dielectric constant $\epsilon' = \frac{G_\epsilon + \left(\frac{\lambda g}{2a}\right)^2}{1 + \left(\frac{\lambda g}{2a}\right)^2}$ (3)

Dielectric loss factor $\epsilon'' = \frac{-B_\epsilon}{1 + \left(\frac{\lambda g}{2a}\right)^2}$ (4)

The ϵ' for both egg white and yolk decreased with increasing temperature and frequency whereas the ϵ'' decreased with increase in temperature and increases with increase in frequency. A linear additive model was used to relate ϵ' or ϵ'' to temperature and frequency.
Its general form of the relationship was

$(\epsilon'$ or $\epsilon'') = p + q.T \pm r.F$ (5)

Where T is the temperature in °C, F is the frequency in GH_Z, and p, q, r are the model coefficients.
Based on empirical values obtained the relationship was derived as
For egg white

$\epsilon' = 72.36 - 0.17.T - 1.75.F$ (6)

$\epsilon'' = 17.26 - 0.19.T + 1.58.F$ (7)

For egg yolk

$\epsilon' = 50.08 - 0.13.T - 1.72.F$ (8)

$\epsilon'' = 13.42 - 0.11.T + 0.65.F$ (9)

The values computed were comparable to those obtained by Ragni et al. for the eggs within the three days of storage [11],[3].Dielectric constants and loss factors obtained for shell and membrane it not change notably with respect to frequency and temperature the values are around 3.4 and .7 for shell & 3.1 and .5 for membrane respectively. Equations 6 to 9 have been represented graphically in figures shown from 4 to 7.

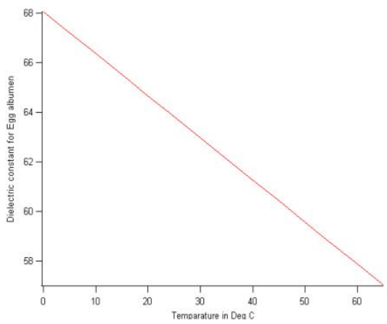

Figure 4 Temperature versus dielectric constant of egg albumen at 2.45GHz

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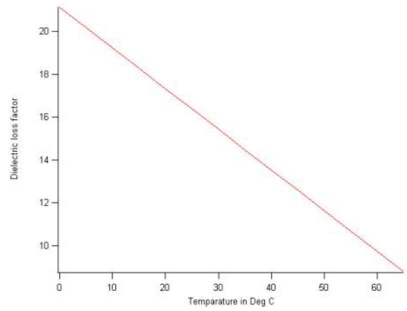

Figure 5 Temperature versus dielectric loss factor of egg albumen at 2.45GHz

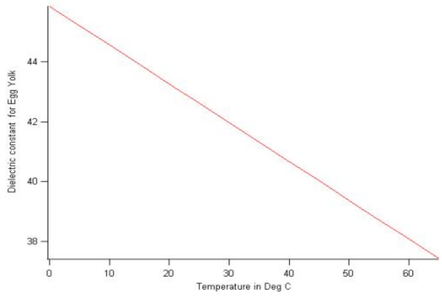

Figure 6 Temperature versus dielectric constant of egg yolk at 2.45GHz

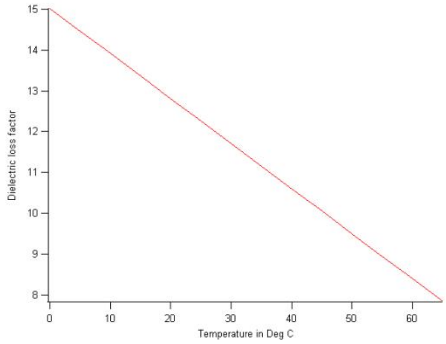

Figure 7 Temperature versus dielectric loss factor of egg yolk at 2.45GHz

2.3 Power Distribution inside the Microwave Oven

2.3.1 Resonant Cavity Approximation

The temperature distribution in an article submitted to microwave radiation is governed by the interaction and absorption of radiation by the medium and the accompanying transport processes due to the dissipation of electromagnetic energy into heat. Thus, modeling of microwave heating involves coupling the models for microwave power absorption and temperature distribution inside the article [8].

In this case the electromagnetic field can be solved exactly. The components of electric field are given by

$$E_x = E_1 \cos(K_x x)\sin(K_y y)\sin(K_z z)e^{i\omega t} \quad (10)$$

$$E_y = E_2 \sin(K_x x)\cos(K_y y)\sin(K_z z)e^{i\omega t} \quad (11)$$

$$E_z = E_3 \sin(K_x x)\sin(K_y y)\cos(K_z z)e^{i\omega t} \quad (12)$$

Where ω is the angular frequency of the micro wave and k_x, $k_{y,}$ and kz are given by

$$k_x = \frac{m\pi}{L_x}, k_y = \frac{n\pi}{L_y}, k_z = \frac{p\pi}{L_z}, (m, n, p = 0, 1, 2, \ldots) \quad (13)$$

L_x, Ly, Lz are dimensions of the cavity and amplitude constants E_1,E_2,E_3 in equations (1-3) are constrained by

$$k_x E_1 + k_y E_2 + k_z E_3 = 0 \quad (14)$$

Which comes from non divergence electric field in charge-free space. It can be seen that by choosing different combinations of (m,n,p) different modes of electric field can be had. Angular frequency of each mode is given by

$$\omega = c\sqrt{k_x^2 + k_y^2 + k_z^2} \qquad (15)$$

For simplicity it has been assumed that food does not perturb the field. The average power density absorbed by the food is

$$< p > = \omega \lim_{x\to\infty}(e) < e^2 >$$

$$\infty < E^2 > \qquad (16)$$

Where Lim (e) is the imaginary part of the dielectric constant of the food.$<E^2>$ can be found by

$$< E^2 > = 1/2(|E_x|^2 + |E_y|^2 + |E_z|^2) \qquad (17)$$

$$< E^2 > = 1/2(E_1^2 \cos^2(K_x x)\sin^2(K_y y)\sin^2(K_z z) +$$

$$E_2^2 \sin^2(K_x x)\cos^2(K_y y)\sin^2(K_z z) +$$

$$E_3^2 \sin^2(K_x x)\sin^2(K_y y)\cos^2(K_z z)) \qquad (18)$$

In order to clearly analyze the power density distribution, it is taken a 29cm*29cm*19cm oven .since the microwave frequency is 2.45 GHz and because of equation ,possible combinations (m,n,p) are (2,4,1),(4,2,1),(2,3,2) and (3,2,2).Note that oven of different size has different possible (m,n,p) combinations. Because of x and y directions are symmetric, here the modes (2, 4, 1) and (2, 3, 2) has been considered. Power density distribution for each mode has been illustrated in figures 8 to 13..

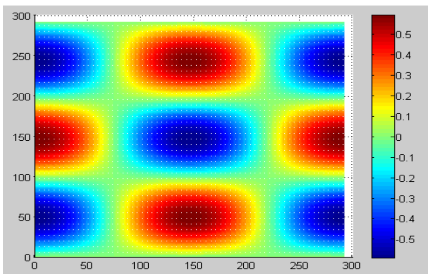

Figure 8 Absorbed power density distribution along X and Y Directions for mode (2, 3, 2) at E1=0

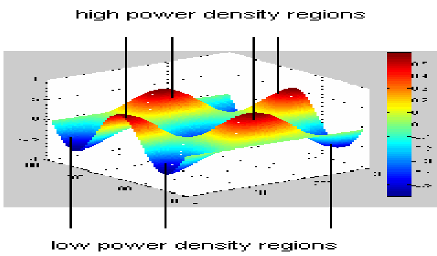

Figure 9 Absorbed power density distribution along X, Y and Z Directions for mode (2, 3, 2) at E1=0

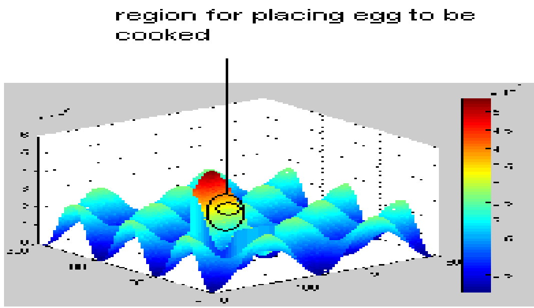

Figure 10 Absorbed power density distribution along X, Y and Z Directions for mode (2, 3, 2) at E2=0

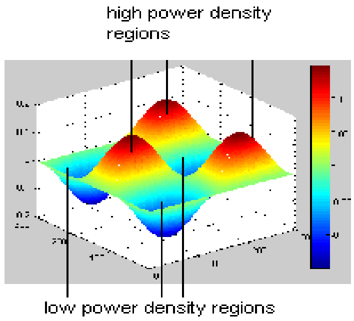

Figure 11 Absorbed power density distribution along X, Y and Z Directions for mode (2, 3, 2) at E1=E2

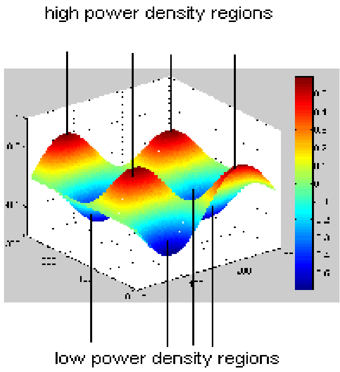

Figure 12 3D Low power density regions identification for mode (2, 3, 2)

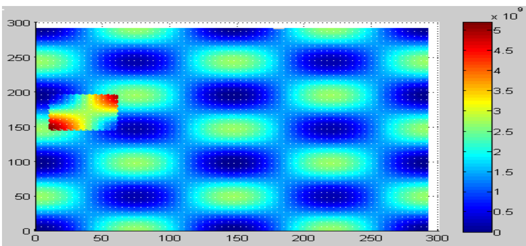

Figure 13 2D Low power density region identification for mode (2, 3, 2)

2.3.2 Experimental design and procedure

A microwave oven consists of:

• a high voltage power source, commonly a simple transformer or an electronic power converter, which passes energy to the magnetron

• a cavity magnetron, which converts high-voltage electric energy to microwave radiation

• a magnetron control circuit (usually with a microcontroller)

•a waveguide (to control the direction of the microwaves)

• a cooking chamber

Prior to measurement, the eggs were cracked carefully and the egg white (35 g) and yolk (20 g) were collected separately in small cylindrical beakers or Pepsi bottle caps. Egg white was homogenized by slow & steady stirring with a glass stick and deal with a single entity for the measurements and not as thin and thick albumen. All measurements were made in triplicates. Egg white from an individual egg formed one replicate and egg yolk from an individual egg formed one replicate. Initially the albumin is placed into small cups of 2.5 cm diameter (Pepsi bottle caps). These cups are placed at specific points estimated to have minimum energy from simulated results. These points are well spaced at half wavelength of the waves in the oven (for 2.4GHz, > 122 mm). By operating the oven at different powers and timing, the level of cooking is measured. The spots where the albumin got cooked fast and started to splatter is noted as high energy points. The spots where the albumin got slowly cooked are marked as points of low energy. Next a full egg with shell is placed at the low energy point and the oven is operated at 40% power for 2 minutes. The egg is found well cooked and there was no explosion.

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Figure 14 Microwave oven used for Experiment

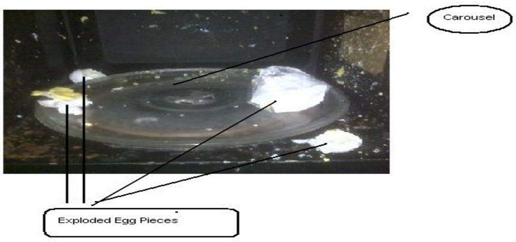

Figure 15 Exploded egg pieces when cooked with carousel

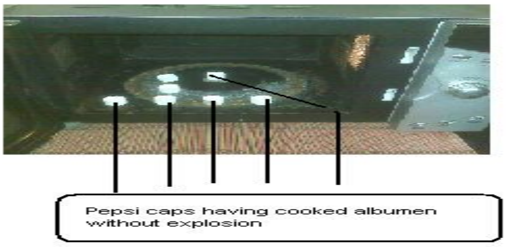

Figure 16 Locating albumen at identified low power regions

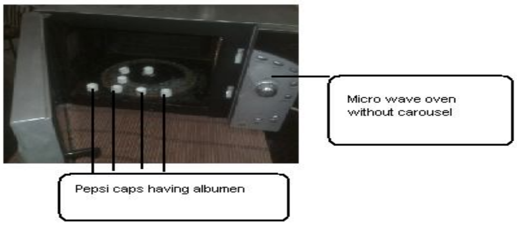

Figure 17 Cooked albumen without splattering

3. Results and Discussions

MATLAB version 7.01 was used to analyze the power distribution inside a microwave oven of 29cm*29cm*19cm with 2.45 GHz frequency. At first, power distribution inside a domestic microwave oven at a frequency of 2.45 Gigahertz was investigated by avoiding carousel.

Two modes of power density distribution (2,4,1) and (2,3,2) were simulated by solving electro- magnetic power distribution equations. At mode (2, 3, 2), Figure 8 shows the absorbed power distribution inside the oven when E1=0 from which it is able to identify positive, zero and negative power regions. Figure 9 shows 3D view of absorbed power distribution inside the oven when E1=0. Figure 10 shows the 3D view of absorbed power distribution when E1=0 and the same is shown for E1=E2 in Figure 11. Figure 12 shows 3D Low power density regions identification for mode (2,3,2) and the same is shown in 2D view in Figure 13. From the analysis it was inferred that at $5.0 < x > 10.0$, $6.0 < y > 9.0$ and $2.5 < x > 5.0$, $5.0 < y > 10.0$ low power density regions were identified for mode (2, 4, 1). Similarly at mode (2, 3, 2) power distribution is depicted at various conditions. From the figure it was interfered that at $3.0 < x > 6.0$, $16.0 < y > 19.0$ and $5.0 < x > 10.0$, $6.0 < y > 8.0$ low power density regions were identified. The figure 12 and 13 depicts a sample low power density region. The findings by simulation results were validated through experimental verification. Commercially available fresh eggs were procured from the local market in refrigerated conditions and allowed to stay at the room temperature for about 3–4 h to reach the ambient temperature.

These eggs were marketed from an egg grading company that uses chlorinated water at ambient temperature to wash the eggs before grading. Samples of egg white and yolk were collected in a similar fashion as for the measurement of dielectric properties.

A domestic microwave (MW) oven (Figure 14) was used for this part of the study. Its main components were: a 2450 MHz microwave generator with adjustable power from 0 to 750 W, waveguides, and a microwave cavity of 29cm*29cm*19cm in which the egg samples were processed. The wave guides were rectangular and TE10 mode of application was used. The microwave generator (magnetron) produced microwaves with varying power densities based on the supplied power. The generated microwaves were guided using the waveguides into the microwave cavity via the above mentioned components in a sequence. All tests were conducted in triplicate and observed that at identified low power density regions egg samples were cooked without explosions which are shown in figures 15 to 17.

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4. Conclusion

Many literatures and socio-care websites are available about Shell eggs exploding in microwave oven and they are demonstrating that the force generated by an exploding egg is great enough to blow open the door of a microwave oven, may cause facial and ocular injuries. They have been done to educate people not to cook eggs in microwave ovens. Keeping this in view it was decided to identify a solution to cook the egg in a microwave oven without explosions to avoid the potential dangers of exploding eggs. Modern microwave ovens are manufactured with turntable to provide uniform heat distribution, when turntable is removed there will be a non uniform heating. This non uniformity has been conceptualized to cook egg in microwave oven by placing the eggs to be cooked in low power density regions. The low power density regions were identified from MATLAB version 7.01 simulation results for which dielectric properties of shell eggs were measured by using microwave test bench. These results were validated through experimental trials. Further it was observed that the low power regions inside the excited microwave oven are available in many layers so that many regions in each layer. Based on this solution egg container to cook many eggs simultaneously in a domestic oven can be designed which can be a safe, efficient and economic mode than conventional cooking methods.

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