Research Article

Modeling Moisture Diffusivity in Deboned Chicken Breast during Deep-Fat Frying

Lamin S Kassama[1*], Michael Ngadi[2]

[*1]Department of Food and Animal Sciences, Alabama A&M University, USA

[2]Department of Bio resource Engineering, McGill University, USA

[*]**Corresponding author:** Lamin S Kassama, Department of Food and Animal Sciences, A-101 Carver Complex Thomas Wing South, Alabama A&M University, 4900 Meridian Street, Normal, AL 35762, USA, Tel: +1 2563724159; Fax: +1 2563725432; E-mail: Lamin.kassama@aamu.edu

Abstract

The effects of frying oil temperature on the effective moisture and oil diffusivies were investigated in this study. Samples of chicken meat were diced into 5 x 3 x 0.3 cm slabs. Liquid and vapor diffusivity were lumped and hence one-dimensional mass diffusion was assumed on an infinite slab. Chicken meat samples were fried at different temperatures (170, 180, and 190°C) in an industrial fryer for periods varying from 5 to 900 s. Fried samples were freeze-dried prior to fat analysis, hence moisture analysis was based on the AOAC standard methods. The effective moisture and oil diffusivies increased with frying oil temperature. Over the range 170 to 190ºC, the effective moisture diffusivity increased from 3.65E-09 to 7.42E-09, and the effective oil diffusivity increased from 9.12E-09 to 3.32E-08 m²/s, based on data from 5 to 900 s frying time. The activation energies were calculated to be 59.5 and 107 kJ/mol for moisture and oil diffusion, respectively.

Introduction

Deep-fat frying is a simultaneous heat and mass transfer process in which the food product with high initial moisture content is subjected to high heat treatment in oil as the medium of heat transfer [1-3]. During this process, heat is transferred to the product by the hot oil, resulting in vaporization of the product's moisture. Heat is conducted through surface contact and as well as by penetration of the hot oil into the product via available pores. Hence, oil may also serve as an active ingredient for supplementary nutrients [4] and influences texture and sensory quality [5]. The parameters influencing the rate and efficiency of the frying process are oil temperature, product moisture content, frying time and physical characteristics of the product [1,2,4,6-9] and surface coatings [10-12].

Oil type and quality are also important to consider as these factors may also influence the physicochemical composition of the product. For example, additives and contaminants in oils can have a marked effect on the organoleptic attributes of the fried products [13] and modify the interfacial characteristic [6]. The characteristics of the food product, i.e. initial moisture content, shape and size, sample weight/frying oil volume and sample surface area/volume ratio, surface tensionsare factors that influence oil penetration and absorption. In consequence, the heat intensity may destroy the heat labile constituents and influence the interactions between nutrients in food and those in the frying oil [14].

Many authors associate frying to drying [7,15-17,8]. The drying process is divided into two distinct phases: the constant rate period and the falling rate period The initial phase, when the surface moisture vaporizes into the cooking medium (oil) has been related to the constant rate period, which causes a considerable amount of turbulence due to boiling at the surface [17]. Throughout the falling rate period, the movement of moisture from the core to the drying surface occurs by diffusion and capillarity action. During this period the boiling front moves towards the internal core of the product. As a result, physicochemical changes such as

solubilization of proteins and denaturation of protein causes pore formation and pore collapse, and structural transformation such as shrinkage of the final fried product [2,6,7,19].

Kinetic modeling can elucidate the transport phenomena involved, and thereby complement the understanding of how the physical properties of the product may change at different combinations of the process variables. This may lead to optimization for a safer product. Several researchers have used kinetic modeling to describe desorption and absorption of moisture and oil, respectively, during deep-fat frying and other processes [7,15,20-23]. Kinetic modeling quantifies rate change, thus correlating the rate parameter to the physical changes that occur as the result of a process. The objective of this study is to determine the effect of frying temperature and time on effective moisture diffusivity and the rate constant of oil uptake in chicken breast slabs, and to develop an empirical model for fat absorption during deep-fat frying chicken breasts.

Moisture diffusion model

Mass diffusion from the chicken breast meat slab was modeled using governing equation of Fick's second law of mass diffusion:
$$\frac{\partial C}{\partial t} = D_e \frac{\partial^2 C}{\partial l^2} \quad (1)$$

Where C is the mass concentration of moisture or oil (kg/kg wb), t is the frying times, D_e is the effective diffusivity of the liquid in question (m²/s) and is the thickness of the sample slab (m). In this study the resistance to moisture transfer at the surface, normally due to convective moisture transfer, was assumed to be negligible since water vapor was rapidly lost from the surface of the frying food. Furthermore, a one-dimensional mass diffusion was assumed on an infinite slab (i.e. the lateral dimensions are much greater than the thickness) of thickness l as shown in Eq (1). The solution to Eq. 1 [24] is based on the following assumptions: uniform initial moisture content, negligible external resistance to moisture transfer. Many authors used Newman's analytical procedure to obtain a solution for Eq 1, hence shown by Eq (2) the Newman solution

$$x = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \left\{ \frac{1}{(2n+1)^2} \left[\exp\left(-\frac{(2n+1)^2 \pi^2}{4} \frac{D_e t}{l^2} \right) \right] \right\} \quad (2)$$

Where x is the mass content (moisture concentration), t is the frying time, l is the half thickness of the slab (m) and n is an integer associated to the sample population. Equation 2 was further simplified by assuming that the missing terms are relatively small. Thus, the expression (Eq 3) reduces to:

$$x = \frac{8}{\pi^2} \exp\left[-\frac{\pi^2 D_e t}{l^2} \right] \quad (3)$$

Materials and Methods

Samples used for the study were chicken breast. The chicken breast meat was acquired from a local chicken product manufacturer and was stored in a freezer at -20°C until used. Frozen samples were thawed in a refrigerator at 4°C for 24 to 36 h when needed. The samples were diced into approximately 5 cm (length) x 3 cm (width) x 0.3 cm (thickness) pieces. Sizing was difficult due to the irregular nature of chicken breast pieces and, as a result, the length and width dimension may vary by approximately ±3 mm.

Frying

Frying was done in a commercial programmable computerized pressure deep-fat fryer Henny Penny Computron 7000 Pressure Fryer (Model 500C, Henny Penny Corporation, Eaton, OH), with a fat/oil holding capacity of about 30 L. A liquid shortening (Can Amera Food, Oakville, ON) was used. A sample to oil weight ratio of 1:480 was maintained, and samples were placed in a wire basket to ensure good contact between the sample and the oil. The fryer was preheated to 170°C for 2 h prior to frying. Samples were fried for a specific period of time, after which they were removed from the fryer, cooled at room temperature, weighed, placed in plastic Zip-Lock sample bags and frozen at –20°C in a freezer prior to further analysis.

Analytical methods

Moisture content

Procedure for the moisture analysis for the fried chicken samples was based on the prescribed method AOAC 960.42 [25]. Samples were place in an oven at 100°C for 18 h as stipulated in the recommended method. The initial mass of the samples prior to oven drying and the final mass of the dried product were determined using a TR-4102D scale (Denver Instrument Co., Denver, CO), hence the moisture content calculated.

Fat content

The freeze-dried fried samples were ground using a blender (Proctor-Silex, model E160B, Picton, ON). The ground samples (2-4 g) were weighed with an electronic scale (TR-4102D, Denver Instrument Co., Denver, CO) and placed in a thimble. Some sea sand was added to the sample in the thimble and mixed with a glass rod. Fat was extracted in a solvent extractor (SER148, Velp Scientific, Usmate, Italy) using petroleum ether. The mass of the glass extraction cups with a few boiling stones was recorded and 50 mL of petroleum ether was added to each cup. The thimbles were then inserted to the magnetic connector of the extraction unit. Procedure followed as recommended by AOAC Method 960.39 [26] and also (SER148, Operation manual). The thimbles were immersed in the boiling solvent for 30 min and then submitted to 60

min of reflux washing and 30 min of drying to recover the solvent. The extracts were further dried in a convection oven (Isotemp 700, Fisher Scientific, Pittsburgh, PA) at 125°C for 30 min. The sample cups were cooled in a desiccator and subsequently weighed. The oil content *(OC)* dry basis was computed for each sample using the following relationship: $OC\ (\%)=\dfrac{\text{mass of oil extracted}}{\text{mass of dried sample}}\ x\ 100$ (4)

Experimental design and statistical analysis

Frying times were randomized within each temperature and triplicates were run sequentially at each time [27]. There were three frying oil temperatures (170, 180, and 190°C), and 14 frying times (5, 10, 15, 20, 30, 45, 60, 90, 120, 150, 180, 210, 240 and 300). Initial fat content was determined on three samples (control). Regression analyses were conducted using SAS software (SAS v.8, Nashville). Duncan's Multiple Range Test (DMRT) was used to separate treatment means (5% level of significance)

Results and Discussion

Moisture diffusivity

Experimental moisture content data was fitted as an exponential function of frying time according to Eq. 5: $x = ae^{-bt}$ (5)

Where a and b are constants. The values of a and b obtained at each temperature are given in Table 1. The rate constant b is associated to the moisture diffusivity by the following relationship: $b = \dfrac{\mathsf{p}^2 D_e}{l^2}$

The rates of moisture loss were observed to be higher at high FOT. The temperature dependence of the rate constant is to be expected due to the energy considerations, similar information has also been reported in studies of fried potatoes [16,28] and deep-fried chicken drums [29] and chicken breast [1,2].

Temp (°C)	Model Parameters				R²
	a (kg/kg wet basis)		b (s⁻¹)		
	Estimated	SE	Estimated	SE	
170	0.81	0.0051	0.0010	0.0001	0.99
180	0.82	0.0085	0.0014	0.0001	0.98
190	0.84	0.0150	0.0020	0.0002	0.97

Temp = Frying temperature; SE = Standard error; R² = Coefficient of determination, a and b are the parameters in Eq 5.

Table 1: Estimated parameters of the moisture diffusion derived from equation 5 model during deep-fat frying of chicken breast.

The observed moisture history at a frying oil temperature of 180ºC is shown in Figure 1 along with the model predictions. The experimental model adequately described the data as indicated by the high R2 and low variability of the parameter estimates (SE's <11% of parameters). The moisture change with respect to time during deep-fat frying is analogous to that obtained in the dehydration of food products [30,31].
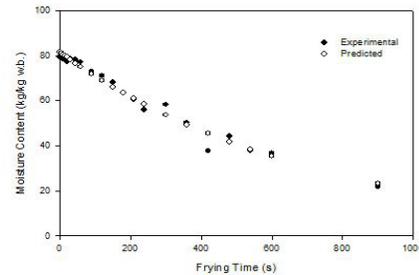
Figure 1: Typical moisture history of chicken breast meat slabduring deep-fat frying.

The effective moisture diffusivities were calculated according to the following relationship (Eq 7) and are model parameters are presented in Table 2: $D_e = \dfrac{b * l^2}{\mathsf{p}^2}$

Temperature (°C)	Effective MoistureDiffusivity (m²/s)	Std Deviation
170	3.65E-09	3.64E-10
180	5.23E-09	5.57E-10
190	7.42E-09	2.11E-10

Table 2: Effective moisture diffusivity values computed from the moisture desorption curve during deep-fat frying of chicken breast meat.

The effect of temperature on moisture diffusivity was evaluated by analysis ofvariance (ANOVA). The moisture diffusivity at different frying oil temperatures were found to differ significantly (P < 0.01), thus diffusion of moisture increases with increase in FOT. The De ranged from 3.65E-09 to 7.42E-09 when chicken meats were deep-fat fried at FOT of 170 to 190°C for 900 s, respectively. Ngadi [29] reported diffusivity coefficients of 1.32E-09 and 1.64E-08 m²/s for deep-fat fried chicken drums at 120 and 180°C, respectively. The diffusivity obtained at 180ºC is an order of magnitude greater than that observed in this study. This may be due to a number of factors, such as different structures of chicken drum compared to breast meat, and heat conduction along the bone to the inner surface of the muscle mass. El-Dirani [10] obtained values of 2.1E-09 to 2.9E-09 m²/s for breaded deep-fried chicken nuggets, which are close to our values. The differences may be the result of the effect of batter. The variations in effective moisture diffusivity are a complex function of the physical properties of the material, such as porosity and pore structure [1-3,6,7,32,33], and of temperature [1,2,6,7,29,34]. Since it is very difficult to measure either liquid and vapor diffusion independently, then we hypothetically assume that the effective moisture diffusivity accounts for both phases. Changes in the physical structure i.e. volumetric shrinkage, may introduce error in the calculated values of apparent diffusivity, since shrinkage is not factored in the model. Since chicken muscle consists primarily of moisture and protein [3,6], denaturation of the protein is another factorwhich contributes to the loss of the moisture binding capacity hence results to increases

in moisture diffusion especially at higher temperatures. The rapid increase in moisture loss from the denatured muscle as a result of FOT may have contributed to shrinkage, increased porosity and thus increased moisture diffusivity [3,7,29,33,35]. Another factor could be the loss of structural integrity of muscle myofibrils at temperatures above 97°C, hence at higher FOT would increase the rate of heat transfer thus may increase its rate deterioration.

The dependence of the effective moisture diffusion coefficient on temperature was assumed to follow the Arrhenius type model (Eq 8): $D_e = D\, e^{\left(-\frac{E_a}{RT}\right)}$

Where D is the apparent diffusivity, E_a is the activation energy, R (8.314 J/K mol) is the universal gas constant, and temperature is absolute (K). The effective diffusivity is plotted against the inverse of temperature in Figure 2. The slope of the line is equals to the activation energy and the intercept is the apparent diffusivity. The ratio of the activation energy to the gas constant (R) is 7275 /°K, and the apparent moisture diffusivity as 5E-07 m²/s. The activation energy for effective moisture diffusivity was calculated to be 59.5 kJ/mol during DFF of chicken breast meat. Activation energies of 24 kJ/mol for DFF of chicken drums and 26 kJ/mol for deep-fried chicken nuggets were reported by El-Dirani [10], respectively. Motarjemi [36] reported activation energies ranging from 34 to 54 kJ/mol for moisture diffusion in mincemeat during oven frying. Low activation energy is an indication of greater ease of moisture transfer and is therefore dependent on the structure of the material and FOT.
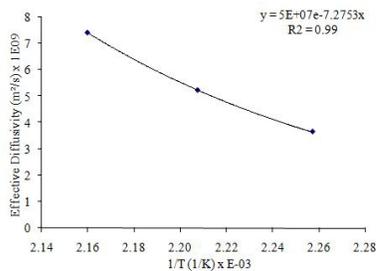

Figure 2: The effective moisture diffusivity of obtained from the moisture profile during deep-fat frying of chicken meat.

Fat uptake

The rate of oil uptake was computed from the following kinetics equation (Eq 9): $C = C_0\left[1 - \exp\left(-k_c t\right)\right]$

Where, k is the rate constant, C is the oil uptake and C_O is the initial oil uptake and t is the frying time (Sec). The results of the estimated kinetic parameters were estimated by non-linear regression and are shown in Table 3. The rate of oil uptake was observed to increase with increase frying temperature [1,2,15,37,38,39]. Frying oil temperature significantly ($P<0.05$) affected the rate of oil absorption. The rate constants for oil uptake were 0.0025, 0.0046, and 0.0091 % oil uptake per second at frying temperatures of 170, 180, and 190°C, respectively.

Temp (°C)	k % Oil Uptake Dry basis		C_0 (s⁻¹)		R²
	Estimated	SE	Estimated	SE	
170	8.13	1.90	0.0025	0.001	0.88
180	10.85	1.34	0.0046	0.0014	0.92
190	9.99	0.62	0.0091	0.0019	0.94

Model Parameters column header spans k and C₀.

Table 3: The rate constants derived for oil uptake profile at different temperatures during deep-fat frying of chicken breast meat slab.

The rate of oil absorption increases with increase in FOT. Figure 3 shows a typical experimental and predicted oil uptake history for samples fried for 180°C. The mathematical model seems to be well fitted to the experimental data as shown by the low standard errors.
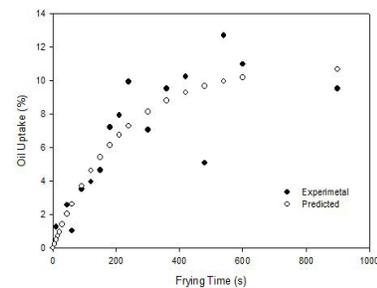

Figure 3: Observed and predicted oil uptake at frying temperature (180°C) during deep-fat frying of chicken breast meat.
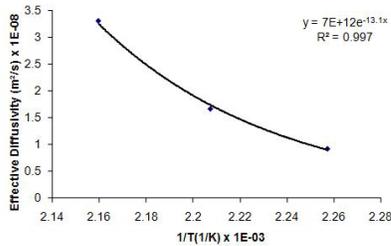
The effective oil diffusivities were computed based on Eq.7 and are shown in Table 4. The effect of frying oil temperature is significant ($P<0.01$) on oil diffusing into the chicken meat during deep-fat frying. The fact that moisture loss and oil uptake are positively correlated, it is an indication that oil diffusivity in chicken may be dependent on moisture diffusivity. The diffusion of oil during deep-fat frying is also dependent of the formation of capillary pores, which occurs as a result of moisture diffusion. The effective oil diffusivity is almost an order of magnitude greater than that of moisture diffusivity computed from the experimental data. This may be due to the fact that the moisture diffusivity involves two-phases (liquid and vapor), most of the moisture movement being due to diffusion of the vapor phase.

Temperature (°C)	Effective Oil Diffusivity (m²/s)	StdDeviation
170	9.12E-09	1.70E-10
180	1.68E-08	1.30E-09
190	3.32E-08	2.3E-09

Table 4: The effective oil diffusivity values computed form the oil absorption curve during deep-fat frying of chicken breast meat.

The apparent oil diffusivity was determined from the graph (Figure 4). The parameters were estimated using Eq. 8. The appar-

ent oil diffusivity was 7.0E-12 m²/s and the activation energy for oil absorption in chicken meat was found to be 107 kJ/mol.

Figure 4: The effective oil diffusivity curve obtained at different frying temperatures during deep-fat frying.

Moisture loss and oil uptake were found to be positively correlated through the first 360 to 420 s. Comparison of predicted oil uptake values using Eq.9 and the experimental values are shown in Table 5. Values predicted by the model were smaller (15 and 40%) than the actual experimental values for the FOT 180, and 190°C respectively. This discrepancy may have been due to the change in physical properties as a result of shrinkage. The effect of the erratic nature of oil uptake after 300 s of frying shown in Figure 3 may have induced some errors estimated by the model.

Temperature	Oil Uptake	
	Predicted	**Experimental**
170°C	4.66	4.28
180°C	7.06	8.14
190°C	9.34	10.04

Table 5: Comparison of predicted and observed oil uptake after 300 s frying at different FOT.

The relationship between moisture loss and oil uptake was positively correlated for up to about 360 s frying time. Therefore, it is possible to predict oil uptake from moisture loss using moisture diffusivity. Both parameters may be dependent on the physical properties of the food product being fried [1,2]. Pore formation due to moisture loss was elucidated by the capillary theory of drying [3,6,40]. The creation of capillary pathways enables oil uptake to occur [6,3,41]. However, it is apparent that increases in moisture diffusivity and pore formation will likely increase the rate of oil uptake.

Conclusions

Moisture loss and oil uptake are mass transfer phenomena that occur during deep-fat frying and are described by an empirical first order kinetic model. Based on the regression models, the effective moisture diffusivity was found to vary from 3.65E-09 to 7.42E-09 while the oil diffusivity ranged from 9.12E-09 to 3.32E-08 m²/s at temperatures ranging from 170 to 190°C, respectively, during deep fat frying of chicken breast meat slab for 900 s. The activation energy was calculated to be 59.5 and 107 kJ/mol for moisture and oil diffusion, respectively. Frying temperatures significantly ($P < 0.01$) affect moisture and oil diffusivity. The intensity of moisture loss and oil uptake increases with frying oil temperature. Better prediction of oil uptake was given during the first 300 s of frying. Change in the physical properties of the food product during deep-fat frying may have influenced the mass transport particularly after 300 s of deep-fat frying.

References

1. Kassama, LS, Ngadi MO (2016a) Relationship between Oil Uptake and Moisture Loss during Deep Fat Frying Of Chicken Breast Meat. Advances in Chemical Engineering and Science 6: 324-334.

2. Kassama, LS, Ngadi MO (2016b) Shrinkage and Density Change of Chicken Meat during Deep-fat Frying. Food and Nutrition Sciences 7: 895-905.

3. Kassama, LS, Ngadi MO (2004) Pore development in chicken meat during deep-fat frying. Lebensmittel-Wissenschaft und-Technologie 37: 841-847.

4. Weber N (1997) Deep Frying. Chemistry, Nutrition, and Practical Applications. Edited by Perkins EG, Erickson MD and 357 pages, numerous figures and tables. AOCS Press, Champaign, Illinois 41 : 247.

5. Pambou-tobiv N, Arab-Tehrany E, Niamayoua RK, Linder M (2016) RSM applied for optimization of deep-fat fried ripe plantain slices and study of oxidation kinetics of oil by DSC and polar methods. Journal Food Sci Technol 53: 269-280.

6. Kassama LS, Ngadi MO (2005a) Pore structure characterization of deep-fat fried chicken meat. Journal of Food Engineering 66: 369-375.

7. Kassama LS, Ngadi MO (2005b) Pore development and moisture transfer in chicken meat during deep-fat frying. Drying Technology 23: 907-923.

8. Moreira RG, Castell-Perez ME, Barrufet MA (1999) Deep-Fat Frying: Fundamentals and Applications. Food Science & Nutrition, MD: Aspen Publishers Inc.

9. Mittelman N, Mizrahi SH, Berk Z (1982) Heats and Mass Transfer in Frying. In: (ed.). McKenna BM Engineering and Food. Elsevier Applied Science Ltd, UK. Pg: 109-116.

10. El-Dirani K (2002) Textural and mass transfer characteristics of chicken nuggets during cooking. M.Sc thesis, McGill University, Montreal, Canada.

11. Balasurbramaniam VM, Chinnan MS, Mallikararjunan P, Phillips RD (1997) The effect of edible film on oil uptake and moisture retention of a deep-fat fried poultry product. Journal of Food Engineering 20: 17-29.

12. Mallikararjunan P, Chinnan MS, Balasurbramaniam VM (1995) Mass transfer in edible film coated chicken nuggets: influence of frying temperature and pressure. In advances in food engineering proceedings of the 4th conference in Food Engineering, (ed.). Narsimhan G, Okos MR, Lombardo S: 107-111.

13. Blumenthal MM (1991) A new look at the chemistry and physics of deep-fat frying. Food Technology 45: 68-71,94.

14. Varela G, Bender AE, Morton ID (1988) Frying of foods: Principles, Changes, New Approaches. VCH publishers, New York.

15. Krokida MK, Oreopoulou V, Maroulis ZB, Marinos-KourisD (2001) Deep-fat Frying of Potato Strips-Quality Issues. Drying Technology 19: 879-935.

16. Costa Rm, Oliveira FAR (1999) Modeling the Kinetics of Water Loss During Potato Frying with a Compartmental Dynamic Model. Journal of Food Engineering 41: 177-185.

17. Singh PR (1995) Heat and Mass Transfer in Foods during Frying. Food Technology. Presented at a symposium sponsored by the IFT Food Engineering Division: 134-137.

18. Mohan Rao VN, Delaney RAM (1995) An Engineering Perspective on Deep-fat Frying of Breaded Chicken Pieces: Mathematical Modeling of Heat and Mass Transfer during Deep-fat Frying of Chicken Parts Can Lead to Improved Quality and Consumer Value. Food Technology. Presented at a symposium sponsored by the IFT Food Engineering Division: 138-141.

19. Wang Y, Ngadi MO, Adedeji AA (2010) Shrinkage of chicken nuggets during deep-fat frying. International Journal of Food Properties 13: 404-410.

20. Van Boekel MAJS, Tijskens LMM (2001) Kinetics Modeling, In Food Process Modeling. (Ed.). Tijsken LMM, Hertog MLATM, Nicolai BM, Wood head Publishing Ltd. Cambridge, England.

21. Gupta P, Shivhare US, BawaAS (2000) Studies on Frying Kinetics and Quality of French Fries. Drying Technology 18: 311-321.

22. Geka V, LambergI (1991) Determination of Diffusion Coefficient in Volume-Changing Systems-Application in the Case of Potato Drying. Journal of Food Engineering 14: 317-326.

23. Moreira RG, Elena Castell-Perez M, Sweat VE (1991) Moisture Loss and Oil Absorption During Deep-fat Frying of Tortilla Chips. American Society of Agricultural Engineers, 2950 Niles Rd., St. Joseph, MI 49085-9659 USA, Paper No. 91-6501.

24. Crank J (1975) The mathematics of diffusion. (2nd edition), Oxford University Press, Oxford, UK.

25. AOAC (1995) Official methods of analysis: 960.42. AOAC International, Gaithersburg, MD, USA.

26. AOAC (1990) Official methods of analysis: 960.39. Association of Official Analytical Chemists, Washington, DC.

27. Gomez AK, Gomez AA (1984) Statistical Procedures for Agricultural Research. (2nd Edition), NY: John Willey and Sons Inc.

28. Baumann B, Escher F (1995) Mass and Heat Transfer during Deep-fat Frying of Potato Slice-I. Rate of Drying and Oil Uptake. Lebensmittel-Wissenschaft and Technologie 28: 395-403.

29. Ngadi MO, Correia LR (1995) Finite element modeling of heat and mass transfer during deep-fat frying of chicken drums. Technical University of Nova Scotia, Halifax, Nova Scotia 37: 4.

30. Karathanos VT (1999) Determination of water content of dried fruits by drying kinetics. Journal of Food Engineering 39: 337-344.

31. Hallstrom B (1992) Mass transfer in food. In: (ed.). food engineering Ch 7: 317-339.

32. Saravacos GD (1986) Mas transfer properties of foods. In: (ed.). Engineering properties of foods 89-132.

33. Karathanos VT, Vegenas GK, Saravacos GD (1991) Water diffusivity in starches at high temperatures and pressures. Biotechnology Progress 7: 178-184.

34. Schoeber WJAH (1976) Regular regimes in sorption processes. Calculation of drying tares and determination of concentration dependent diffusion coefficients 16: 183.

35. Xiong X, Narsimhan G, Okos MR (1992) Effect of composition and pore structure on binding energy and effective diffusivity of moisture in porous food. Journal of Food Engineering 15: 187-208.

36. Motarjemi Y (1989) Determination of moisture diffusivity in foodstuffs. In Trend in food Science 139-143.

37. Rahimi J, Ngadi MO (2015) Surface ruptures of fried batters as influenced by batter formulations. Journal of Food Engineering 152: 50-56.

38. Krokida MK, Oreopoulou V, Maroulis ZB (2000) Water Loss and Oil Uptake as a Function of Frying Time. Journal of Food Engineering 44: 39-46.

39. Gamble MH, Rice P, Seldman JD (1987) Relationship between Oil Uptake and Moisture Loss During Frying of Potato Slices from c.v. Record UK Tubers. International Journal of Food Science and Technology 22: 233-241.

40. McDonough CM, Lee JK, Gomez MH, Waniska RD, Rooney LW (1992) Corn Starch Changes During Tortilla and Tortilla Chip Processing.Institute of Food Technologists Annual Meeting, New Orleans 69: 275-279.

41. Guillaumin R (1988) Kinetics of Fat Penetration in Food. In: Frying of Food, Principles, Changes and New Approaches: 82-89.