

Moisture diffusivity in chicken drum muscle during deep-fat frying

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Ngadi, M.O. and Correia, L.R. 1995. **Moisture diffusivity in chicken drum muscle during deep-fat frying.** *Can. Agric. Eng.* 37:339-344. Effective moisture diffusivity (D_e) in rectangular muscle slices cut from chicken drum, during deep-fat frying, was determined as a function of moisture and temperature. The experimental apparatus consisted of a temperature controlled oil bath and a wire screen basket on which the muscle slices were placed. The oil bath was maintained at temperatures of 120, 140, 160, and 180°C. The mean initial moisture content of muscle samples was 3.33 kg water/kg dry solids (standard deviation = 0.16 kg/kg). Samples were immersed in frying oil for up to 1920 s. Values of effective moisture diffusivity, determined using regular regime theory, ranged from 1.32×10^{-9} to 1.64×10^{-8} m²/s for moisture range of 0.06 to 3.33 kg water/kg dry solids and oil bath temperatures of 120 to 180°C. Variation of effective moisture diffusivity was exponential with respect to moisture. Temperature effect on effective moisture diffusivity was modelled using an Arrhenius type equation. Estimated activation energy for moisture diffusion was 24 kJ/mol.

Keywords: moisture diffusivity, chicken drum muscle, deep-fat frying, immersion frying

La diffusivité effective (D_e) de l'eau dans la chair de poulet (tranches rectangulaires obtenues dans la cuisse) a été déterminée en fonction de la teneur en eau et de la température. Les échantillons étaient placés sur un treillis métallique et ensuite immergés dans un bain thermostatique contenant de l'huile à frire. L'huile était maintenue à des températures de 120, 140, 160, et 180°C. La teneur en eau initiale moyenne des échantillons était de 3,33 kg d'eau/kg masse sèche (variance = 0,16 kg/kg). Les échantillons étaient immergés dans l'huile pour une durée de 1920 s. La théorie de diffusion en régime régulier a été utilisée pour calculer la diffusivité effective. Des valeurs de D_e variant de $1,32 \times 10^{-9}$ à $1,64 \times 10^{-8}$ m²/s ont été obtenues pour des teneurs en eau variant de 0,06 à 3,33 kg d'eau/kg masse sèche et des températures d'huile variant de 120 à 180°C. La diffusivité effective variait exponentiellement avec la teneur en eau. Une équation de type Arrhenius a été utilisée pour représenter l'effet de la température sur la diffusivité effective. L'énergie associée à la diffusion de l'eau a été estimée à 24 kJ/mol.

INTRODUCTION

Deep-fat (or immersion) frying is a common unit operation in the food service and snack food industries. A significant portion of total calorific intake of American consumers is from deep-fat fried foods (Nawar 1985; Handel and Guerrieri 1990). Deep-fat frying is the process in which food is cooked in an oil medium. Heat transfer and mass transfer, flavour, texture, and chemical changes occur during frying. Moisture is also transferred out of the food product. It has been a challenge to balance doneness with moisture loss (Morgan et al. 1991) such that optimum moisture is retained while the food is well cooked. Since frying temperatures are typically

above 100°C, it is expected that moisture is transferred from porous solid food material as liquid and vapour (Thomas et al. 1980). Effective moisture diffusivity is the total diffusivity of moisture in liquid and vapour forms.

Literature data on mass diffusivity in solid food materials are very limited and vary considerably due to lack of a standard method of measurement (Saravacos 1986). Estimation of moisture diffusivity in starchy foods (Xiong et al. 1991; Karathanos et al. 1990, 1991), fruits and vegetables (Singh et al. 1984), prepared intermediate moisture porous foods (Tong and Lund 1990) and comminuted meat products (Mittal and Blaisdell 1984) have been reported. Estimation of moisture dependent diffusivity is typically a cumbersome and laborious task (Tong and Lund 1990). Thus estimation of moisture diffusivity during deep-fat frying is further complicated by the complexity of food-oil interaction and typically high frying oil temperatures.

Methods of measuring mass diffusivity can be classified as internal or external. Internal measurement approaches include labelling of migrating components or measurement of changes in optical properties of material during a diffusion process (Naesens et al. 1981, 1982). Nuclear magnetic resonance (NMR) has recently been used for internal measurements of diffusivity (Schrader and Litchfield 1990; Ruan et al. 1990). The use of NMR is limited because of its high cost. External measurements of diffusivity seem to be more widely used and are typically based on the monitoring of average concentration of material as a function of diffusion time (Luyben et al. 1980; Singh et al. 1984; Tong and Lund 1990; Karathanos et al. 1990). Regular regime sorption theory has been reported to be a simple experimental procedure for measuring diffusivity as a function of concentration (Singh et al. 1984). The theory as proposed by Schoeber (1976) is that following a transient diffusion in a homogenous mixture, the shape of the concentration profile and its change with time becomes independent of initial concentration. The existence of a regular regime period can be shown from the analytical solution of Fick's diffusion equation (Schoeber and Thijssen 1977). Regular regime theory in diffusion measurements can be applied if the regular regime curve is known at desired temperatures for the case of constant surface concentration. The objectives of this study were to investigate the existence of regular regimes during deep-fat frying of chicken drum and to mathematically model the variation of effective moisture diffusivity as a function of moisture and frying oil temperature during deep-fat frying of chicken drum muscle.

MATERIALS AND METHODS

Fresh chicken drum samples were obtained from a local producer and stored at -23.4°C (S.D. = 0.13°C) until ready for use. The chicken drum samples were individually packed in freezer bags before storage. All the chicken drum samples were used within one month of storage. Before each experiment, a frozen chicken drum sample was thawed at a refrigerator temperature of about 4°C for 24 h. A thawed chicken drum sample was de-skinned and the muscle part was cut into rectangular slices of dimension $65 \times 25 \times 3$ mm. Thin slices were used to minimize temperature and moisture gradients within sample during frying. The Hobart model 610 slicer (Hobart Corporation, Troy, OH) was used for slicing the chicken muscle while a pair of scissors was used for trimming. The rectangular slice dimensions were verified using a vernier calliper. Initial moisture contents of all samples used in experiments were between 3.03 and 3.58 kg/kg dry matter (mean = 3.33, S.D. = 0.16).

The experimental set-up consisted of a modified home supercool fryer (Type 3617M, Tefal, Dijon, France), which was used as an oil bath. The oil bath heating system was modified to be controlled by a logic level three-state proportional controller which delivered heat at 0, 20, and 100% of full power rating (Ngadi 1995). A datalogger model ADC-1 (Remote Measurement Systems, Seattle, WA) and a Toshiba T1000 laptop computer were used for the control system. Preliminary experiments verified that the specified control system was adequate in controlling oil temperature within 2°C of set-point temperature.

A steel wire screen basket of 0.8 mm wire diameter, mesh opening of 8 mm and with about 9% of product area in contact with the wire mesh was provided to hold muscle slices while immersed in oil during diffusivity experiments. Oil bath temperatures of 120, 140, 160, and 180°C were used. At each temperature, eight muscle samples were individually fried at different times of 4, 8, 12, 16, 20, 24, 28, and 32 min. The experiments were replicated three times. The sequence of the various frying times, as well as the order of frying oil temperatures, were completely randomized using the SAS randomization procedure (SAS Institute Inc. 1988). Moisture content of the muscle slices before and after frying for the various times was measured using the oven method according to ASAE standard S353.2 (ASAE 1989). Samples of reduced initial moisture contents of about 1.88 kg/kg dry matter were obtained by freeze drying chicken muscle at plate temperature of 20°C . The thickness and other dimensions of dried samples were measured using a vernier calliper. The density was measured by an air comparison pycnometer (Model 930, Beckman Instruments Inc., Fullerton, CA).

The effective diffusivity of chicken drum muscle was computed from the moisture-time experimental data by employing the procedure of Luyben et al. (1980) and Singh et al. (1984) as per the following sequential steps:

1. A regression model was fitted to the aforementioned data to obtain chicken muscle moisture content as a function of frying time:

$$m = f(t) \quad (1)$$

where:

- m = moisture content of a chicken drum muscle slice (kg/kg dry matter), and
- t = frying time (s).

2. The moisture flux, j_m , relative to the moving interface was expressed as (Ngadi 1995):

$$j_m = -\frac{W_{ds}}{A} \frac{dm}{dt} \quad (2)$$

where:

- j_m = moisture flux (kg/m^2),
- W_{ds} = mass of dry sample (kg), and
- A = mass transfer area (m^2).

3. The flux parameter, F , a dimensionless parameter related to the moisture flux during frying, was calculated as:

$$F = \frac{j_m \rho_{ds} X_{ds}}{D_o \rho_{so}^2} \quad (3)$$

where:

- ρ_s = solid density of sample (kg/m^3),
- X_{ds} = dry sample thickness (m), and
- $D_o \rho_{so}^2$ = the combined term with numerical value equal to 1, introduced for dimensional similarity ($\text{kg}^2 \cdot \text{m}^{-4} \cdot \text{s}^{-1}$).

The solid density was calculated from the expression for bulk density (Eq. 9) at zero moisture content.

4. Using steps 1 to 3 above, the moisture flux parameter, F , was expressed as a function of moisture to obtain a regular regime curve:

$$F = f(m) \quad (4)$$

5. The regular regime curve (Eq. 3) was differentiated to obtain:

$$X = d \ln(F) / d \ln(m) \quad (5)$$

6. A regression equation of the average Sherwood number, Sh_d , for the moisture diffusion process was obtained from the graph of Sh_d versus X for diffusion in a slab geometry as presented by Luyben et al. (1980):

$$Sh_d = f(X) \quad (6)$$

7. The effective moisture diffusivity of chicken drum muscle was then computed for the different frying oil temperatures using:

$$D_e = D_o \cdot \frac{\rho_{so}^2}{\rho_b^2} \frac{d}{dm} \left(\frac{2F}{Sh_d} \right) \quad (7)$$

The Arrhenius model was used to describe the temperature dependence of the effective moisture diffusivity. The linear and non-linear regression analyses were conducted using the REG and the NLIN procedures of SAS (SAS Institute Inc. 1988). Analysis of data was performed using a HP 9000 835S mainframe computer.

RESULTS AND DISCUSSION

For all samples, moisture content decreased during deep-fat frying to an average moisture of 0.06 kg/kg dry matter during the frying period of 1920 s. Moisture change during deep-fat frying was similar to other dehydration processes such as air drying (Karathanos et al. 1990). The best regression model for Eq. 1 was:

$$m = a \cdot e^{-bt} \quad (8)$$

where a and b are constants. Values of the model parameters are presented in Table I. The exponential model adequately described the data with most standard error of estimates below 10% of each parameter estimate. Figure 1 shows plots of typical observed data for three independent experiments, and a well fitted curve of the moisture frying time relationship.

Bulk density of muscle slabs, ρ_b (kg/m³), measured for 48 samples as a function of moisture content was modelled using Eq. 9 (the coefficient of determination, $R^2 = 0.803$, the probability greater than the F -value, $p = 0.0001$, and the degrees of freedom = 28).

$$\rho_b = 761 + 208 m - 38 m^2 \quad (9)$$

Standard error	17	28	8
$Pr > t $	0.0001	0.0001	0.0001

Bulk density decreased as moisture content of the slab decreased from its initial value to zero.

Figure 2 shows the plots of regular regime curves i.e. flux parameter, F , versus moisture content, m , at the frying temperature of 140°C for muscle slabs with initial moisture contents of 3.33 and 1.88 kg/kg dry matter. The regular regime curves for muscle samples at the initial moisture content of 3.33 kg/kg dry matter fairly coincided with that for muscle at the lower initial moisture content of 1.88 kg/kg dry matter. All regular regime curves are presented in Fig. 3. These results agree with the pattern of regular regime curves reported for moisture sorption and desorption in other food materials, namely, potato (Luyben et al. 1980); apple (Luyben et al. 1980; Singh et al. 1984), white bread, muffin, and biscuit (Tong and Lund 1990). The result verifies the exist-

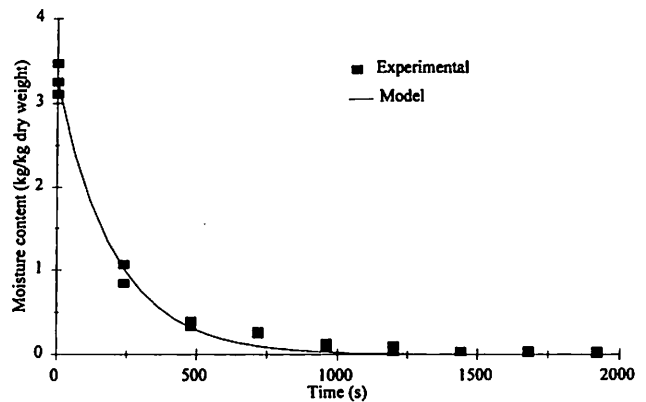


Fig. 1. Moisture content of chicken drum muscle (sample size = 3) during frying at 140°C oil temperature.

ence of a regular regime in deep-fat frying and indicates some form of similarity between deep-fat frying and drying.

The best regression model for Eq. 6 was:

$$\ln(Sh_d) = 1.59 + 0.2590 \ln(X) - 0.0482 (\ln(X))^2 \quad (10)$$

Standard error	0.002	0.00291	0.00166
$Pr > t $	0.0001	0.0001	0.0001

For Eq. 10 the coefficient of determination was 0.9994, $p >$ the F -value was 0.0001, and the degrees of freedom were 12.

The effective moisture diffusivity values, computed using Eq. 7 ranged between 1.32×10^{-9} and 1.64×10^{-8} m²/s for the moisture and frying oil temperature ranges of 0.06 to 3.33 kg/kg dry basis, and 120 to 180°C, respectively. Variation of effective moisture diffusivity is a complex function of the physical properties of food (Saravacos 1986) as well as process temperature (Schoeber 1976). Effective moisture diffusivity generally increased with higher food material porosity due to increased moisture mobility (Karathanos et al. 1990). The effective moisture diffusivity values obtained in this study were relatively higher in comparison to corre-

sponding values for minced meat (Motarjemi 1989) and meat emulsion (Mittal and Blaisdell 1984) (Table II) presumably due to higher process temperatures, food structure, and the method used.

Figure 4 shows the variation of computed effective moisture diffusivity as a function of moisture content during deep-fat frying at different oil temperatures. At all the frying oil temperatures, the effective moisture diffusivity initially decreased slightly and then increased as the moisture content of the chicken drum muscle decreased from the initial value of 3.33 kg/kg dry matter to 0.06 kg/kg dry matter. The effective moisture diffusivity increased rapidly at lower values of moisture content and at higher frying oil temperatures. The

Table I: Regression parameters of moisture as a function of frying time

Frying oil temperature (°C)	Model parameters				MSR	MSE
	a (kg/kg db)		b (s ⁻¹)			
	Est	SE	Est	SE		
120	3.276	0.122	2.173×10^{-3}	1.456×10^{-4}	24.86	0.051
140	3.258	0.059	4.840×10^{-3}	2.006×10^{-4}	17.65	0.010
160	3.395	0.033	7.213×10^{-3}	2.155×10^{-4}	17.85	0.003
180	3.203	0.049	1.431×10^{-2}	6.744×10^{-4}	15.90	0.007

Est is estimate; SE is standard error;
MSR is mean sum of regression; MSE is mean sum of error
Degrees of freedom = 25

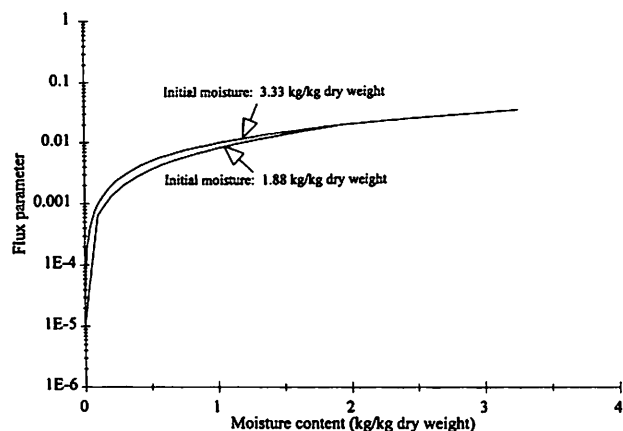


Fig. 2. Regular regime curves for chicken drum muscle fried at 140°C oil temperature.

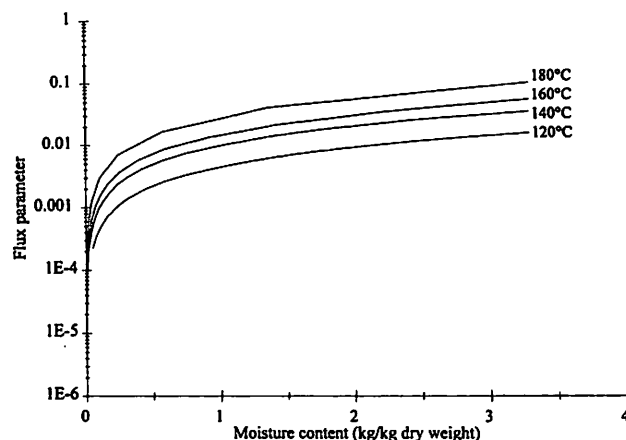


Fig. 3. Regular regime curves for chicken drum muscle at various frying temperatures.

Table II: Comparison of reported moisture diffusivity in some muscle foods

Material	Moisture (kg/kg db)	Temperature (°C)	D_e ($10^{-10} \text{ m}^2/\text{s}$)	Reference
Minced bovine meat	3.07 - 3.26	5 - 30	0.10 - 0.20	Motarjemi (1989)
Meat emulsion	1.86	42 - 58	0.58 - 1.61	Mittal and Blaisdell (1984)
Meat emulsion	1.86	58 - 81	1.12 - 5.89	Mittal and Blaisdell (1984)
Chicken muscle	0.06- 3.33	120 - 180 ^a	13 - 164	This study

^a Oil temperature

results indicate the effects of two opposing phenomena on chicken-drum-muscle moisture diffusivity during deep-fat frying.

Chicken muscle is largely composed of muscle and protein. Some moisture is bound to hydrophilic groups in muscle protein by electrostatic attraction forces, which are progressively weaker with increasing distance from the hydrophilic groups (Kropf and Bowers 1992). At the outset of deep-fat frying, as with other dehydration processes, the loosely attached moisture on the muscle surface was presumably first detached by evaporation from the wet surface (Bengtsson et al. 1976). Progressive depletion of free moisture apparently increased mass transfer resistance and thus decreased effective moisture diffusivity (Xiong et al. 1991). This phenomenon was observed in this study by the small initial decrease in effective moisture diffusivity at high moisture contents.

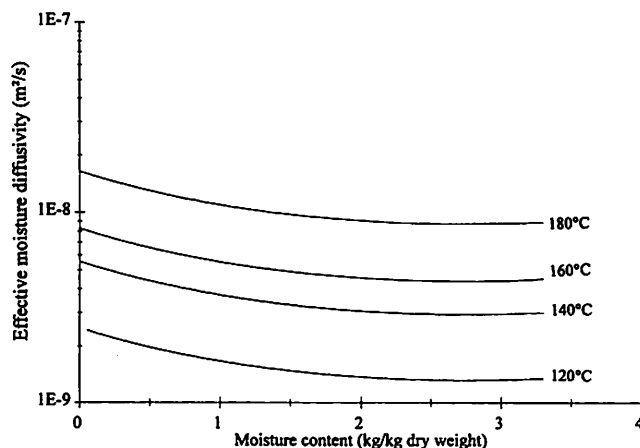


Fig. 4. Effective moisture diffusivity of chicken drum muscle versus moisture content at various frying oil temperatures.

As frying progressed, muscle protein denaturation was presumably initiated at a product temperature of about 50°C (Kijowski and Mast 1988), thus decreasing the moisture binding capacity of muscle proteins. The available moisture was rapidly evaporated at the higher temperature of the denatured muscle resulting in increased effective moisture diffusivity (Karathanos et al. 1991; Xiong et al. 1991). Also, the loss of structural integrity of the muscle myofibrils at or near transverse elements, which occurred when muscle was heated to 97°C (Schaller and Powrie 1972), may have also contributed to the increased moisture diffusivity at the higher frying oil temperatures.

The effective moisture diffusivity obtained in this study represents an overall average mass transfer property of moisture in chicken drum muscle, which includes liquid and vapour diffusion. It is postulated that at the onset of deep-fat frying, moisture transfer within the muscle structure was

mainly by liquid diffusion. However, as frying proceeded, the muscle temperature increased while moisture content decreased. Hence, moisture diffusion especially at higher frying oil temperatures was due to vapour diffusion as illustrated by the observed sharper increase in the plots of effective diffusivity versus moisture. The interaction of temperature and moisture content on food structure largely affected moisture diffusivity of chicken drum muscle.

The effective moisture diffusivity of chicken drum was fitted using an Arrhenius type model as:

$$D_e = 8.35 \times 10^{-6} \exp\left(-\frac{2930}{T} - 0.561m + 0.092m^2\right) \quad (11)$$

where D_e = effective moisture diffusivity (m^2/s).

For Eq. 11, the degrees of freedom for residuals were 131, the mean sum of squares for residuals was 4.50×10^{-18} , the asymptotic standard errors for the pre-exponent, reciprocal of temperature, moisture, and moisture squared parameter estimates were $4.54E-6$, 240, 0.159, and 0.0596, respectively.

The ratio of the activation energy of moisture diffusion in chicken drum muscle and the universal gas constant was $2930 K^{-1}$, from which the activation energy for effective moisture diffusivity was calculated as 24 kJ/mol. The activation energy obtained in this study was independent of moisture content. Activation energy is the energy required to facilitate change in effective diffusivity within given conditions (Laidler 1978). Mortajemi (1989) reported activation energy values of 34 to 54 kJ/mol for moisture diffusion in minced bovine meat at a lower temperature range of 5 to 30°C. Low activation energy is indicative of greater ease of moisture transfer in a given material. This obviously is dependent on material structure, moisture content, and process temperature. The low activation energy obtained in this study may be attributed to the higher frying oil temperature and differences in muscle structure.

CONCLUSION

Estimated effective moisture diffusivity in chicken muscle samples during deep-fat frying ranged between 1.32×10^{-9} and $1.64 \times 10^{-8} m^2/s$. Effective moisture diffusivity increased with increasing frying oil temperature from 120 to 180°C. Decreasing moisture content from 3.3 kg/kg dry matter to 0.06 kg/kg dry matter generally increased moisture diffusivity. An Arrhenius type equation was used to model variation of effective moisture diffusivity as a function moisture and frying oil temperature. The estimated activation energy of 24 kJ/mol was independent of muscle moisture content.

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