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RESEARCH ARTICLE

Mathematical modeling of moisture loss, oil uptake and colour kinetics during deep fat frying of onion slices

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ABSTRACT

Effects of frying temperature, frying time and pre-fry-drying time on kinetics of moisture loss and oil uptake during frying were studied. Colour development during frying were also measured in terms of Hunter L, a, b parameters. Onion slices of 3 mm thickness were used for frying at 135, 150 and 165^{o}C. The experimental data on moisture loss and oil uptake were fitted to a first order exponential model and kinetic co-efficients for mass transfer were calculated. Kinetic co-efficients were found to increase from 0.595 - 0.803 min^{-1} for moisture loss and from 0.38 - 0.563 min^{-1} for oil uptake with increase in frying temperature. Temperature dependence of kinetic co-efficients for moisture loss and oil uptake values were described by Arhenious type equation with activation energies of 1.88 x 10^3 KJ/kg mol for moisture loss and 2.3 x 10^3 KJ/kg mol for oil uptake, respectively. As the pre-fry-drying time increased from 0 to 60 min, kinetic co-efficients were found to decrease from 0.71 to 0.617 min^{-1} for moisture loss and 0.442 to 0.326 min^{-1} for oil uptake. 60 minutes pre-drying reduced the oil content by 22.88 per cent. The mathematical modeling of colour parameters with respect to time and of frying and pre-fry drying time shown best fit with polynomial equation of third order. Two distinct periods (colour development and degradation) of colour changes observed as indicated by Hunter a and b values. During colour development period Hunter a and b values increased with temperature indicating golden surface colour.

KEY WORDS : Colour kinetics, Deep fat frying, Mass transfer, Modelling, Onion slices

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INTRODUCTION

Deep fat frying is one of the most important unit operations in catering and food processing operations (Blumenthal and Stier, 1991) and is a traditional cooking method which achieves desirable textures and flavors in a variety of foods (Mohan and Delaney, 1995). During frying heat transfer and mass transfer takes place simultaneously (Moreira *et al.,* 1995 and Vitrac *et al.,* 2002). As the heat transferred from frying medium to the food water comes out of the food. Oil is not only heat transfer medium but also enters the food. The driving force for mass transfer was the pressure gradient caused by the conversion of water into steam.

Fried products contain a substantial amount of fat, some as much as more than 45per cent oil content (Funami and Funami, 1999 and Saguy and Pinthus, 1995), because food, especially vegetable origin are low in fat and high in moisture content, absorb large amount of fat during deep fat frying. Excess consumption of fat is considered as the key dietary contributor to coronary heart disease and perhaps cancer of the breast, colon and prostate (Browner *et al.,* 1991).

Excess fat uptake by the food is not desirable for consumer as well as manufacturer. Various factors that affect the oil uptake during deep fat frying are composition (Ng *et al.*,1957), frying temperature, duration (Gamble *et al.*,1987 and Krokida *et al.,* 2000) product shape and size (Bouchon and Pyle, 2004; Baumann and Escher, 1995; Gamble and Rice, 1988b), initial moisture content (Yamsaengsung and Moreira, 2002; Gamble and Rice, 1988a; Rice and Gamble, 1989) and pre-frying treatments (Krokida *et al.,* 2001a and Moyano and Berna, 2002) and pre-frying operations like steaming (Kawas and Moreira, 2001) etc. The required characteristics of fried foods (final water content, browning and texture) are the result of both raw material properties and of processing (Vitrac *et al.,* 2000). Colour development (due to browning reactions) is considered as one of the important parameter of fried foods. Knowledge on colour development parameters during deep fat frying will permit improvement of product appearance through proper selection of processing conditions (Baik and Mittal, 2002). Recently, many investigations were carried out with the aim of lowering oil uptake during deep fat frying. Reduction in oil content in the final product was reported by addition of hydrocolloids to foods (Rimac *et al.*, 2004) and edible coatings on the foods before frying (Williams and Mittal, 1999; Albert and Mittal, 2002). Debnath and Bhat (2000) reported that blending equal proportion of gelatinized starch to the chickpea flour to be very effective in reducing the oil content in fried product.

According to Gamble and Rice (1987), there was a decrease in oil content in the fried product when initial dry matter content in potato slices was manipulated by microwave drying or hot air drying before frying. The initial solid content can be increased by drying the slices prior to frying by hot air drying as well as infrared drying to produce a product with lower oil content (Smith and Davis, 1965). Studies on effect of pre-drying on the quality of French fries have been reported earlier (Krokida *et al.,* 2001b). Effect of pre-drying on the kinetics of moisture removal and oil uptake was reported by Gupta *et al.* (2000).

Quality of breaded and battered fried onion rings were reported by Duling *et al.* (1998) and Gennadios *et al.* (1997). Hansen (1998) reported that effect of frying temperature was significant on colour development during frying of onion slices. But in all their experiments they have used battered coatings, where the coatings have major role in moisture and oil transfer phenomena and colour of final product.

Crisp fried onion is used in the preparations in pizzas, ethnic foods, ready meals, sandwiches, salads, specialty breads (Jennings, 1997) and also used as an ingredient in convenience foods like dehydrated curry mixes (Das Gupta *et al.,* 2003).

Although fried onion is a popular ingredient used for many preparations, reports on the mass transfer phenomenon (moisture loss, oil uptake) during deep fat frying are not available. These data can be used for standardization of the frying process, mass transfer characteristics and product optimization with respect to quality attributes, like oil and moisture content, colour of fried product.

The present work was taken upto study the effect of frying temperature and pre-drying on i) mass transfer kinetics of moisture loss and oil uptake during deep fat frying of onion slices ii) Colour changes during frying.

EXPERIMENTAL PROCEDURE

Preparation of onion slices:

Onions were procured from the local market. Each onion was bisected and sliced to 3.0 $\pm$ 0.2 mm thick using an adjustable hand slicer. Onions of nearly similar size were only selected (average dia. at middle portion = 58 $\pm$ 6.2 mm) to reduce its effect on the experimental results. The initial moisture content of the onion slices was 6.82 kg/kg db. 100 g of sliced onion was taken for frying experiments.

Pre-fry-drying of the slices was carried out in a cabinet dryer (Kilburn Pvt. Ltd., Bombay) at 60^{o}C with a load density of 2.3 kg per square meter area of the tray. Samples were removed from the dryer after 20, 40, 60 min and used for frying.

Deep fat frying:

A laboratory scale deep fat fryer (Continental Equipment (I) Ltd, Bangalore, India) with temperature controller to control within ± 2°C, was used for deep fat frying. The fryer was equipped with a stainless steel basket in which sample is placed. Refined soybean oil was used as frying medium. The sample to frying medium ratio is maintained at 1:20 w/v throughout the experiments. After each experiment oil level was checked and replenished with fresh oil. The oil was completely replaced with fresh one after 2 h of frying. Oil temperatures were set at 135°C, 150, 165°C and were monitored using a digital thermometer with J type thermocouple probe of 1.6 mm dia. (Spectrochem Pvt Ltd, Mumbai, India).

The samples were fried for 1, 2, 3, 5, 7, 9 , 11 and 13 min. The fried samples were strained for 1 min and surface oil was wiped out immediately using a blotting paper. Samples were packed in polypropylene pouches after cooling to room temperature.

Analytical methods:

The moisture content was determined by keeping powdered samples in a vacuum oven at 70°C till a constant weight was achieved. Oil content was determined by Soxhlet extraction method using petroleum ether (40-60°C). Duplicate samples were analyzed and averages were reported on dry weight basis.

Kinetic co-efficients for moisture loss and oil uptake:

The experimental data of moisture loss and oil uptake with respect to frying time were fitted to a first order exponential model as given by Krokida *et al.* (2000).

$$(X_t - X_e)/(X_0 - X_e) = \exp(-K_x t) \qquad \text{.........(1)}$$

$$Y_t = Y_e\,[1-\exp(-K_y t)] \qquad \text{.........(2)}$$

where Kx and Ky are the kinetic co-efficients for moisture loss and oil uptake. X and Y represent the moisture and oil content, Xe and Ye represents equilibrium values. Xt and Yt represents the concentration at different frying times. Xo is the initial concentration.

Colour:

Hunter L, a and b colour values of fried onion slices were measured with a tristimulus colorimeter (Chroma flash, Datalab India Ltd, Silvasa, India). The three colour co-ordinates ranged from L=0 (darkness) to L=100 (brightness), -a (greenness) to +a (redness) and -b (blueness) to +b (yellowness) colour was measured in replicates of 4 samples and average values were reported. The colorimeter was calibrated using a standard white tile supplied with the instrument.

Statistical analysis:

All the experiments were performed in triplicate and the analysis of variance (ANOVA) was carried out for the values of the experiments to find out the significant difference (at 5% significant level) using statistical software (Systat 12.0).

EXPERIMENTAL FINDINGS AND ANALYSIS

The results obtained from the present investigation as well as relevant discussion have been summarized under following heads :

Effect of frying temperature on moisture loss and oil uptake:

The data showing the effect of frying temperature on moisture loss and oil uptake of onion slices has been presented in Fig. 1 and 2, respectively. As the frying time increased the moisture content decreased and oil uptake increased exponentially and reached a constant value (which is termed as equilibrium value) after 9 min of frying time. As the frying temperature increased from 135°C to 165°C the equilibrium moisture content decreased from 0.25 - 0.031 kg/kg db and oil content increased from 0.413 -0.565 kg/kg db.

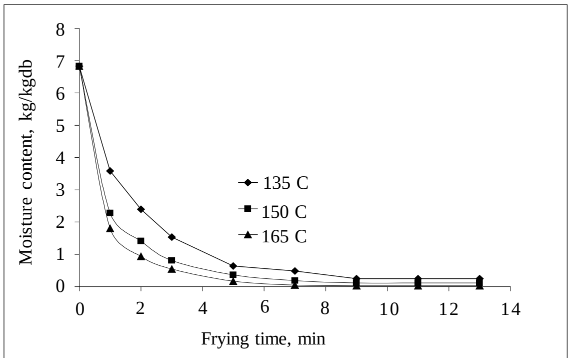

Fig. 1 : Effect of frying temperature on moisture content of onion slices during frying

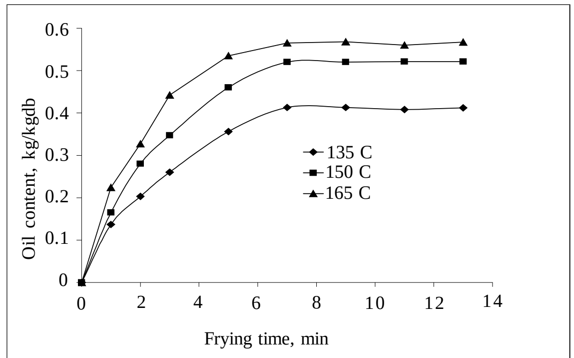

Fig. 2 : Effect of frying temperature on oil uptake of onion slices during frying

The moisture loss and oil uptake was faster at 165°C than 135 and 150°C as expected. The oil uptake was found to be high compared to any other fried products, this may be because of high initial moisture content and high surface area of the onion slices. Selman (1989) reported that higher surface to mass ratio of the food increased oil absorption during deep fat frying. Bhat and Bhattacharya (2001) also reported that a high surface to mass ratio of small boondi resulted high final oil content compared to large size boondi.

Kinetic co-efficients for moisture loss and oil uptake were obtained as per equations 1 and 2 and were shown in Table 1.

Kinetic co-efficients increased from 0.595 to 0.803 min^{-1} for moisture loss and 0.38 to 0.563 min^{-1} for oil uptake with increase in frying temperature. Increase in kinetic co-efficients may be attributed to the increase in amount of heat energy transferred to the slice with increase in frying temperature.

The temperature dependence of kinetic constants (Kx and Ky) were described by the following Arhenious type equation

$$Kx = Ax \exp [-Ex/RT] \quad \ldots\ 3$$

Table 1 : Parameters of first order exponential model for moisture loss and oil uptake at different temperatures **(Initial moisture content, Xo=6.82 kg/kg db)**

Frying temperature (°C)	Xe (kg/kg db)	Kx (min^{-1})	Regression co-efficient (R^2)	Ye (kg/kg db)	Ky (min^{-1})	Regression co-efficient (R^2)
135	0.37	0.595	0.989	0.413	0.380	0.988
150	0.188	0.71	0.991	0.52	0.442	0.975
165	0.052	0.803	0.955	0.565	0.563	0.992

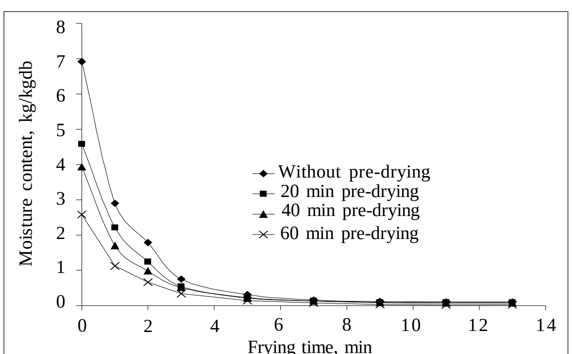

Fig. 3 : Effect of pre-fry-drying on moisture content of onion slices during frying

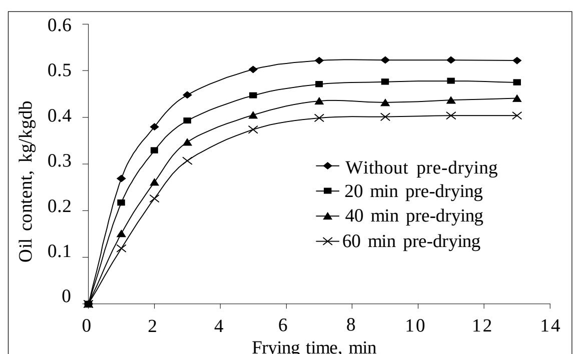

Fig. 4 : Effect of pre-fry-drying on oil uptake of onion slices during frying

Ky = Ay exp [-Ey/RT] ….. 4

where Ax and Ay are constants, Ex and Ey are activation energies for moisture loss and oil uptake (with a regression co-efficient of 0.995 and 0.961), respectively. R is the gas constant (R = 8.32 KJ/Kg mol K). T is the absolute temperature in ^oK. The values of Ax, Ay are 3.18 min^{-1} and 3.06 min^{-1} and Ex, Ey are 1.88 x 10^3 KJ/kg mol and 2.3 x 10^3 KJ/kg mol (Obtained from the intercept and slope of the plot of 1/T Vs –ln Kx or Ky as shown in Fig.9).

Effect of pre-fry drying in moisture loss and oil uptake:

The effect of pre-drying time on the moisture loss and oil uptake of onion slices has been shown in Fig. 3 and 4, respectively. As the pre-drying time increased from 0 to 60 min, the initial moisture content decreased from 6.82 kg/kg db to 2.58 kg/kg db.

The decrease in initial moisture content reduced the equilibrium content of oil from 0.52 kg/kg db to 0.401 kg/kg db corresponds to a decrease of 22.88 per cent oil content.

During frying the changes in moisture loss and oil uptake were fitted to first order exponential model as per Eq. 1 and 2. The kinetic co-efficients and equilibrium moisture and oil contents were shown in Table 2. Increase in pre-drying time resulted in decrease of kinetic co-efficients from 0.71 min^{-1} to 0.617 min^{-1} (for moisture loss) and from 0.442 min^{-1} to 0.326 min^{-1} (for oil uptake).

Colour changes:

Effect of frying temperature on the surface colour changes (Hunter L, a and b) of the onions slices were presented in Fig. 7 and 8. The lightness value (L) decreased from 54.54 to 35-29.9 as frying time and/or temperature increased.

Hunter a and b values showed two distinct periods of colour changes, colour development period and degradation period.

Development of golden surface colour during frying can be related to increase of redness (a) and yellowness (b). Redness (a) of onion slices increased significantly during frying (due to browning reactions) and was found to

Table 2 : Parameters of first order exponential model for moisture loss and oil uptake at different pre drying times (Frying temperature = 150°C)

Pre drying time (min)	Xo (kg/kg db)	Xe (kg/kg db)	Kx (min^{-1})	Regression co-efficient (R^2)	Ye (kg/kg db)	Ky (min^{-1})	Regression co-efficient (R^2)
0	6.82	0.188	0.71	0.991	0.521	0.442	0.975
20	4.58	0.088	0.692	0.989	0.476	0.404	0.980
40	3.93	0.081	0.659	0.985	0.432	0.356	0.981
60	2.58	0.032	0.617	0.980	0.401	0.326	0.970

Xo = Initial moisture content , Xe = Equilibrium moisture content, Ye = Equilibrium oil content,
Kx = Kinetic rate constant for moisture loss, Ky = Kinetic rate constant for oil uptake

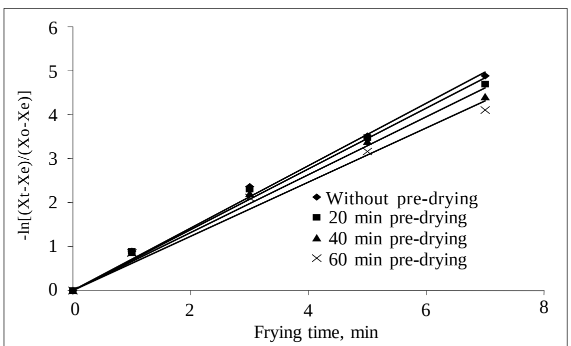

Fig. 5 : Plot for the calculation of kinetic co-efficient for moisture loss at different pre-fry-drying times

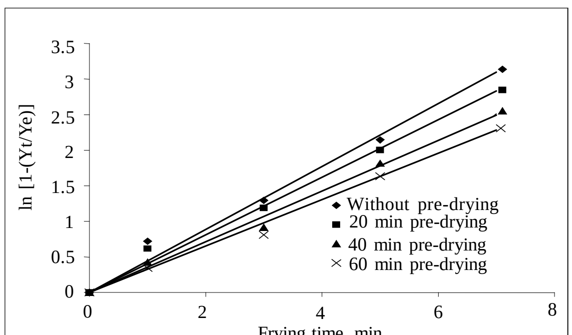

Fig. 6 : Plot for the calculation of kinetic co-efficient for oil uptake at different pre-fry-drying times

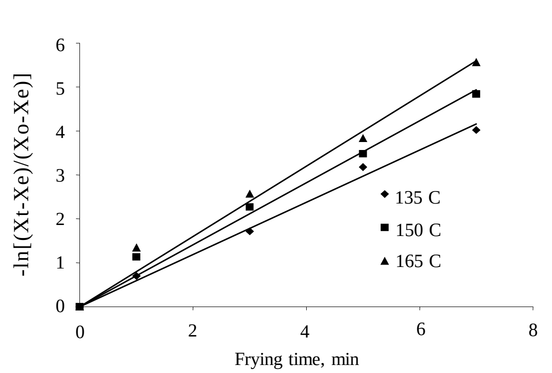

Fig. 7 : Plot for the calculation of kinetic co-efficient for moisture loss at different frying temperatures

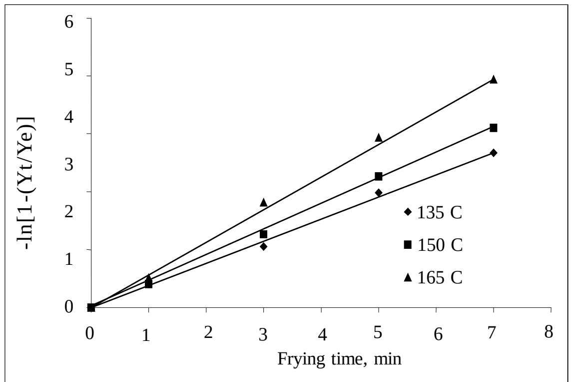

Fig. 8 : Plots for the calculation of kinetic co-efficient for oil uptake at different frying temperatures

increase with frying temperature also. The increase was faster at 165°C, indicating faster colour development at higher temperature. A peak redness value was observed at 5, 8.5 and 10.5 min at frying temperatures of 135, 150 and 165 °C, respectively and it was the indication of golden surface colour. Then further frying caused the rapid browning reactions and decreased the ‘a’ value. Declining (which is termed as degradation period) was also found to be faster at higher temperature.

The ‘b’ value first increased with frying time resulting maximum golden colour at 6,7 and 11 min at temperatures of 135, 150 and 165, respectively. Yellowness development was faster at higher temperature. A decline in ‘b’ was observed on further frying which is termed as degradation period.

The results of colour changes (value a and b) with distinct colour development and degradation periods were in good agreement with the results obtained by Baik and Mittal, 2002 while studying surface colour during deep fat frying of tofu.

Effect of pre drying on the surface colour changes of onion slices were shown in Fig. 5 and 6. The lightness value of onions slices decreased due to pre fry drying process indicating darkening of the product. The L value of

Table 3: Modeling of colour parameters (Hunter L,a,b) of third order polynomial equation at different frying temperatures and pre drying times

Treatments	Colour parameter L	R^2	Colour parameter a	R^2	Colour parameter b	R^2
T_1	$Y=0.033x^3 + 0.862x^2 - 7.043x + 53.42$	0.984	$y = -0.005x^3 + 0.090x^2 + 0.349x + 0.394$	0.996	$y = -0.005x^3 + 0.054x^2 + 0.701x + 2.696$	0.996
T_2	$Y=0.044x^3 + 1.103x^2 - 8.428x + 52.47$	0.959	$y = -0.003x^3 - 0.035x^2 + 1.409x + 0.281$	0.983	$y = -0.000x^3 - 0.096x^2 + 1.659x + 2.457$	0.994
T_3	$y = -0.047x^3 + 1.163x^2 - 8.737x + 51.54$	0.926	$y = 0.010x^3 - 0.321x^2 + 2.71x - 0.050$	0.951	$y = 0.010x^3 - 0.337x^2 + 2.769x + 2.431$	0.993
D_1	$y = -0.045x^3 + 1.131x^2 - 8.550x + 52.40$	0.955	$y = -0.003x^3 - 0.019x^2 + 1.313x + 0.351$	0.994	$y = 0.000x^3 - 0.120x^2 + 1.766x + 2.412$	0.990
D_2	$y = -0.038x^3 + 0.978x^2 - 7.792x + 51.39$	0.971	$y = -0.000x^3 - 0.101x^2 + 1.680x + 0.760$	0.990	$y = 0.005x^3 - 0.213x^2 + 2.081x + 3.095$	0.985
D_3	$y = -0.040x^3 + 1.024x^2 - 7.995x + 50.64$	0.978	$y = 0.003x^3 - 0.175x^2 + 1.954x + 1.279$	0.985	$y = 0.007x^3 - 0.246x^2 + 2.073x + 3.897$	0.990
D_4	$y = -0.046x^3 + 1.139x^2 - 8.562x + 49.56$	0.972	$y = 0.012x^3 - 0.361x^2 + 2.673x + 2.083$	= 0.994	$y = 0.012x^3 - 0.344x^2 + 2.221x + 5.449$	0.994

Y is the colour parameter and X is time in minutes
Frying temperatures = T_1=135 deg C, T_2=150 deg C, T_3=165 deg C),
Pre-drying time D_1 = 0 minutes, D_2 = 20 minutes, D_3 = 40 minutes, D_4 = 60 minutes

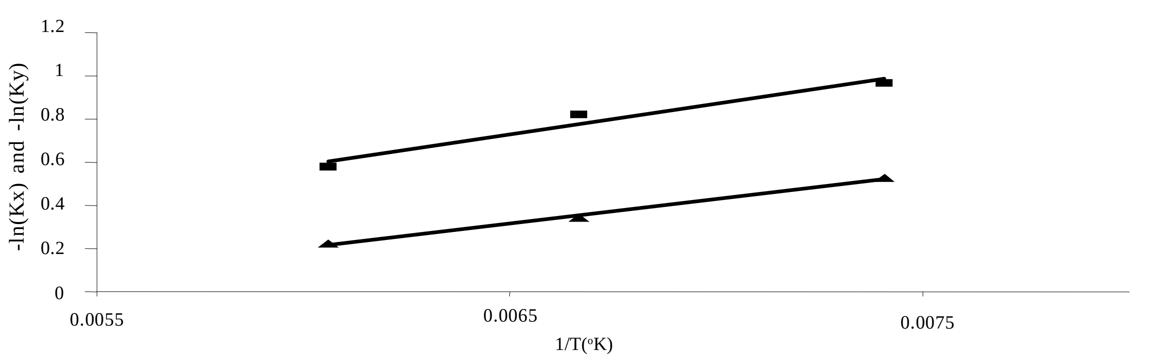

Fig. 9 : Plot of –ln (Kx) and –ln (Ky) Vs inverse absolute temperature (▲-moisture loss, ■- oil uptake

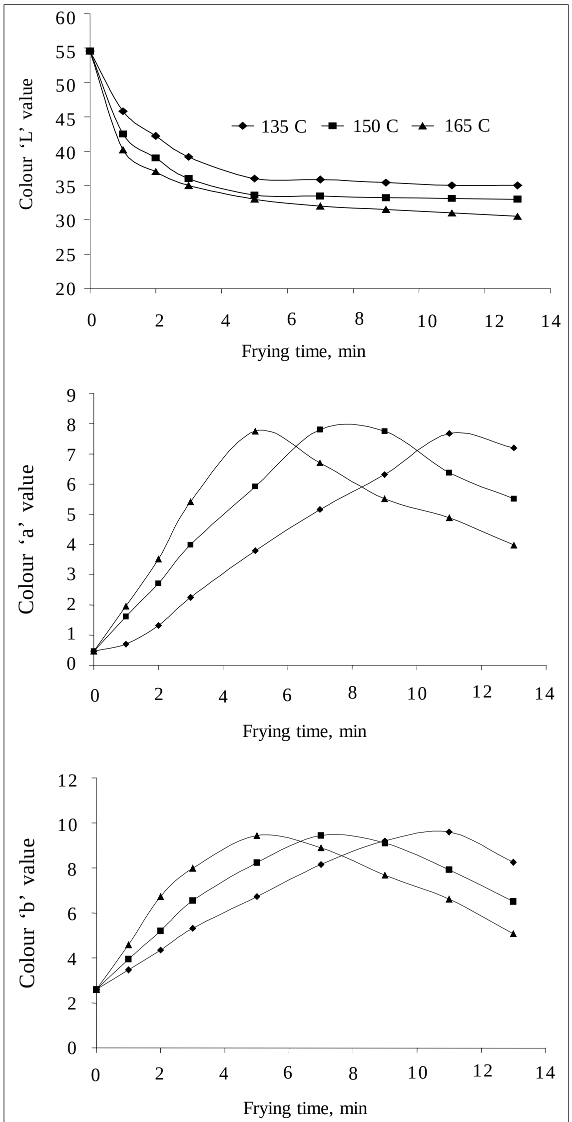

Fig. 10 : Effect of frying temperature on colour parameters (Hunter L, a and b) of fried onion slices

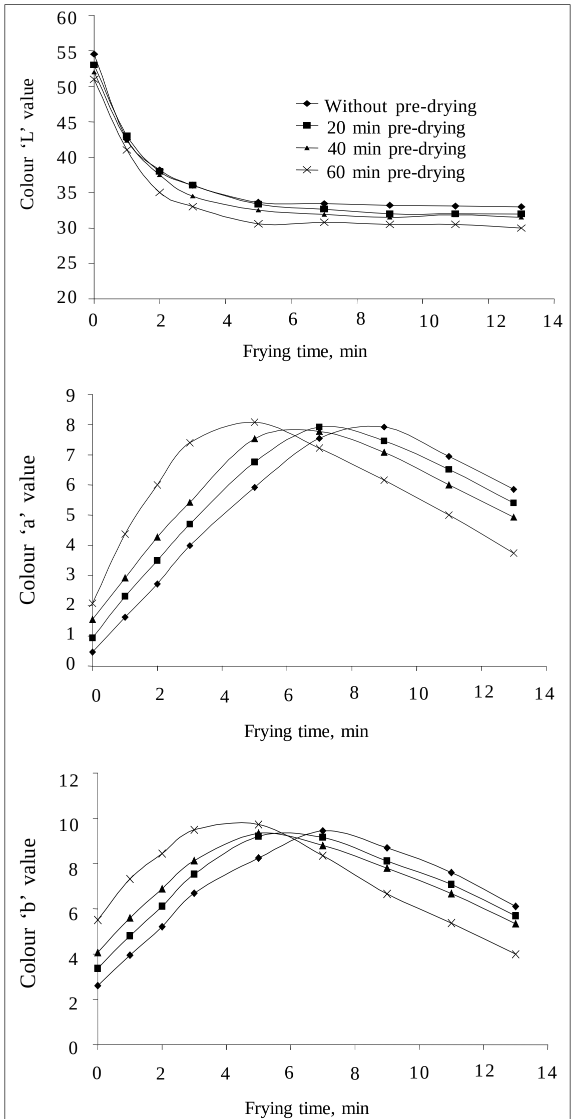

Fig. 11 : Effect of pre-fry-drying time on colour parameters (Hunter L, a and b) of fried onion slices

onion slices was found to be lowest in case of 60 min pre drying time. Hunter 'a' value (redness) of the product increased during drying continued to increase during frying also. Increase of redness was faster only after 40 min pre drying. Hunter 'b' value (yellowness) of the product also followed similar trend as 'a' value.

Mathematical modeling of colour changes:

The colour parameters (Hunter L,a,b) are modeled using polynomial equations of second and third order. The third order polynomial equations with R^2 values above 0.90 are given at Table 3. The second order equations not shown in the table considering the lower level of R^2 vales, *i.e.*, below 0.90.

Conclusion :

Frying behaviour of onion slices in the temperature range of 135°C-165°C was characterized. The results obtained showed that the frying temperature and frying time had a major effect on moisture and oil content. The kinetics of mass transfer (for moisture loss and oil uptake) showed that data is following first order exponential model. Kinetic co-efficients (Rate constants) for moisture loss and oil uptake were found to increase with temperature. Temperature dependence of rate constants were described by an Arhenious type relation, with activation energies of 1.88×10^3 KJ/ kg mol, 2.3×10^3 KJ/kg mol for moisture loss and oil uptake, respectively. Reducing the initial moisture content by pre drying was found to be effective in reducing final oil content by 22.88 per cent. The pre-drying also affected rates of mass transfer phenomenon (of both moisture loss and oil uptake) during frying. Hunter L value decreased as frying temperature and/or frying time increased. Two distinct periods of colour changes observed as indicated by Hunter a and b values. A golden surface colour was developed during frying and colour development was faster at higher temperature. Colour changes taken place during pre-drying found to deteriorate further during frying, however changes in redness and yellowness was significant only after 40 min pre-drying. Modelling of colour parameters found best fit with polynomial equation of third order. The modeling of the kinetics would be useful for the process standardization in the mechanized operation of food frying.

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