Measurement and prediction of thermal properties of pantoa during deep-fat frying

Neethu KC, F Magdaline Eljeeva Emerald and Heartwin A Pushpadass

Abstract: Thermal properties of pantoa were determined during deep-fat frying (DFF) in sunflower oil at 125-145°C. Thermal conductivity (k: 0.357 to 0.199 Wm⁻¹K⁻¹), thermal diffusivity (α: 0.105×10⁻⁶ to 0.140×10⁻⁶ m²s⁻¹) and volumetric specific heat (Cₚ: 3.275 to 1.401 MJm⁻³K⁻¹) were measured simultaneously using dual probe heat pulse technique. Thermal conductivity and volumetric specific heat of pantoa decreased as the moisture content decreased, while thermal diffusivity increased with the decrease in moisture content. Empirical models were also developed as a function of moisture content, fat content and temperature of frying of pantoa. It was found that moisture content was inversely related to fat content during the progress of frying. The thermal properties and the developed models would be useful in the mathematical modeling of heat transfer in pantoa during DFF.

Keywords: Dairy product, Deep-fat frying, Pantoa, Thermal conductivity, Thermal diffusivity, Volumetric specific heat

Introduction

Nowadays, ‘sweetmeats’ in which heat-desiccated milk solids (khoa) or heat-acid coagulated milk solids (chhana) play an important role are very popular. Pantoa, a traditional sweetmeat based on chhana, finds its origin in the Eastern parts of India. It is similar to gulabjamun of North India in flavour and appearance but differ in its textural attributes. Pantoa is prepared by blending chhana, sometimes admixed with khoa, with maida (refined wheat flour), baking powder and other optional ingredients followed by deep-fat frying (DFF) in ghee or vegetable oil and soaking in sugar syrup. Pantoa is typically characterized by a light to dark brown crust and creamish white soft core. The product has optimum sweet nutty flavour with a firm body and moderately chewy texture (Neethu et al. 2015).

The thermal properties of the food material vary continuously due to moisture loss, oil uptake and temperature change during DFF. Thermal conductivity, thermal diffusivity and specific heat are the primary thermal properties of food materials. Thermal conductivity can be defined as the amount of heat transferred by conduction through unit cross section area per unit time due to unit thermal gradient existing perpendicular to the area. The importance of thermal conductivity is to predict or control the heat flux in foods during processing operations such as frying, cooking, drying, pasteurization, sterilization, freezing, etc. Thermal diffusivity indicates how fast heat propagates through a material while heating, frying, canning or cooling and is used to calculate time-temperature distribution in the material. Specific heat is the ability of a food product to store heat relative to its ability to conduct (loss or gain) heat. It is based on how much energy is needed to raise the temperature. Thermal properties of foods are important for the design of optimal processing systems, modeling processes, prediction and control of changes that occur in foods during thermal processing and in calculation of energy requirement. Sensory attributes of foods and energy savings during processing are also affected by thermal properties in addition to processing and preservation.

Experimental studies on determination of thermal properties of fried foods such as meat balls (Ateba and Mittal 1994), tortilla chips (Moreira et al. 1995b), sausages (Dincer and Yildiz, 1996), potato (Sahin et al. 1999), pastry (Williams and Mittal 1999), shrimp (Ngadi et al. 2000), chicken slabs (Vélez-Ruiz et al. 2002), tofu (Baik and Mittal 2003) and donuts (Vélez-Ruiz and Sosa-Morales 2003) were stated in literature. However, no study has been reported on thermal properties of pantoa during DFF. Information on thermal properties of pantoa is significant for modeling and simulation of heat transfer during DFF. Therefore, the present
study was carried out to determine the thermal properties of pantoa during DFF and to develop empirical models for the thermal properties of pantoa as a function of frying conditions, moisture and fat contents.

Materials and Methods

Preparation of pantoa

Pantoa was made according to the procedure outlined by Neethu et al. (2015). Khoa and chhana were blended in 4:5 ratio along with other ingredients, such as, refined wheat flour (3%), semolina (3%), arrowroot powder (3%), ground sugar (0.7%) and baking powder (0.3%) to a smooth and homogeneous dough. Khoa and chhana were prepared according to the method described by Rajorhia and Srinivasan (1979) and Kumari et al. (2015), respectively. Exactly 15 g of dough was taken and rolled into balls and deep-fried in sunflower oil at temperatures of 125, 135 and 145°C for 8 min in a mini-master electric fryer (Model: CMF-6/I/E, Continental Equipment India Pvt. Ltd., Bengaluru).

Analysis of samples

During the progress of frying, pantoa samples were taken once in 60 s for the analysis of moisture content, fat content and thermal properties.

Determination of moisture content

Fried pantoa ball was mashed using pestle and mortar. Exactly 5 g of the mashed pantoa was taken and the moisture content of pantoa was determined using the method prescribed for hard cheese (AOAC, 2000).

Estimation of fat content

About 1 g of the ground sample was transferred to 100 mL beaker. The fat content was determined using the Mojonnier fat extraction apparatus as explained in BIS (1981). Ten mL concentrated hydrochloric acid was added to the samples for digestion followed by the addition of 10 mL of ethyl alcohol. Fat was extracted with 25 mL each of diethyl ether and petroleum ether. The extraction was repeated 3 times and the superficial layer was decanted to a beaker of predetermined weight. The solvents were evaporated completely in a water bath. The residue obtained was dried in hot air oven at 100±2°C for 1 hour.

Measurement of temperature

The thermocouple probes were used to measure the temperature of the frying oil and core temperature of pantoa which in turn was connected to a digital temperature indicator (Sigma Automation, Bengaluru, India).

Measurement of thermal properties

KD2 Pro thermal properties analyzer (Decagon Devices Inc., Pullman, Washington, USA) with dual needle SH-1 sensor was used to determine the thermal conductivity, thermal diffusivity, volumetric specific heat and thermal resistivity simultaneously. The device works on the principle of line heat source probe theory of transient heat transfer analysis. One needle has a line heat source and the other is a thermocouple. The gap between the thermocouple and the needle is filled by an epoxy material of high thermal conductivity. When electric current is passed through the heater, the probe gets heated at a constant rate and the temperature of the probe inserted at the centre of the food sample was monitored over time. The thermal properties are calculated by observing the dissipation of heat from a line heat source at a known voltage. The length and diameter of the needle are 30 and 1.3 mm, respectively with the spacing of 6 mm. The measurement ranges are: thermal conductivity: 0.02 to 2 W m⁻¹ K⁻¹; thermal diffusivity: 0.1 to 1 mm² s⁻¹ and volumetric specific heat: 0.5 to 4 MJ m⁻³ K⁻¹ with the accuracy of 10%. The SH-1 is well-suited for solid and granular materials.

The thermal properties of pantoa were measured after cooling the samples to ambient temperature. The probe was pierced into the centre of pantoa and kept undisturbed while measuring. The probe was calibrated using a two-hole Delrin block method, before conducting the actual trials.

Statistical analysis and modeling of thermal properties

All the experiments for each treatment were conducted in triplicate. Two-way analysis of variance (ANOVA) was done to determine if there is a significant effect of different frying temperature (p d’ 0.05) on thermal properties using SPSS (v.15.0) (SPSS Inc., Chicago, IL, USA). Statistical analysis was conducted to study the effects of frying time and temperature, moisture content and fat content on thermal properties. A multiple linear regression model was formulated for predicting the thermal properties of pantoa in similar conditions. Adjusted coefficient of determination (Adjusted R²) was used to evaluate the adequacy of the models.

Results and Discussion

Relationship between moisture content and fat content

The correlation between moisture and fat contents of pantoa during frying is shown in Fig. 1. With the progress of frying time the moisture content decreased whereas the fat content increased with increase in frying temperatures. Thus, the moisture and fat contents were negatively correlated. Similar trend was observed by other researchers (Gamble et al. 1987; Rice and Gamble, 1989; Moreira et al. 1995a; Shih et al. 2001; Garayo and Moreira, 2002; Vélez-Ruiz et al. 2002; Nema and Prasad, 2004; Tungsangprateep and Jindal, 2004; Budžaki and Šeruga, 2005; Tan and Mittal 2006).
Fat content was predicted as a function of moisture content as given in Eq. 1.

\[ F = -0.275M + 39.841 \]

Eq. (1)

where ‘F’ is the fat content (% w.b.) and ‘M’ is the moisture content (% d.b.). The correlation coefficient between moisture and fat contents was -0.986.

As soon as the pantoa was immersed in hot oil, surface heating occurred by natural convection between the hot oil and the product. Then, the moisture was released as a stream of steam bubbles and the moisture content started to drop rapidly. The outer surface became dry with the formation of crust providing a diffusion gradient. The oil gets absorbed into the crust and migrated into the core. Similar mechanism was observed in potato chips during frying (Nema and Prasad 2004).

Thermal conductivity (k)

Fig. 2 depicts the thermal conductivity of pantoa samples measured at different frying time-temperature combinations. As frying time and temperature increased, the thermal conductivity decreased. After 480 s of frying, it decreased to 0.232, 0.231 and 0.214 Wm⁻¹K⁻¹ at 125, 135 and 145°C, respectively, from 0.355 Wm⁻¹K⁻¹. The drop in moisture content, increased oil uptake and higher porosity might be the reason for decrease in ‘k’ values with progress of frying. Similarly, thermal conductivity of chhana varied from 0.331 to 0.442 Wm⁻¹K⁻¹ in the temperature range of 40-47°C, moisture 52-59%, fat 20-25% and protein 17-25%. It increased with increase in temperature, moisture and protein content in chhana. The thermal conductivity was inversely proportional to fat content (Nayak and Sawhney, 2004). The thermal conductivity of khoa with moisture content of 32-68% and temperature range of 10-90°C varied between 0.259 and 0.473 Wm⁻¹K⁻¹. Thermal conductivity of paneer, with the moisture content of 41-57% and temperature range of 6-40°C was found to be in the range of 0.212 to 0.353 Wm⁻¹K⁻¹ (Jayakumar, 1998). Our results were consistent with the findings of Moreira et al. (1995b) for tortilla chips. The thermal conductivity of tortilla chips reduced from 0.23 to 0.09 Wm⁻¹K⁻¹ when fried at 190°C in soybean oil. Baik and Mittal (2003) observed that the ‘k’ of tofu ranged from 0.24 to 0.43 Wm⁻¹K⁻¹ at 5-80°C. Fat acted as insulator and reduced heat conduction, thereby lowering the ‘k’ values (Ngadi et al., 2000). Heldman and Lund (1992) postulated that thermal conductivity was a function of moisture and structure of a food product.

Multiple linear regression analysis was done to formulate a model for thermal conductivity of pantoa incorporating frying time, frying temperature, moisture content and fat content as independent variables. The tests of significance for frying temperature and time were insignificant, and hence, were removed from the model. In fact, the adjusted \( R^2 \) of the multiple regression model improved, when temperature and time were excluded from the model (Eq. 2). The underlying basis for the lack of temperature effect could be due to the influence of ‘k’ of water. This was also stated by Sweat (1975), who concluded from several models that temperature had little effect on ‘k’. The reduced multiple linear regression model for thermal conductivity of pantoa as a function of moisture and fat contents is presented below.

\[ k = 0.513 - 0.012F + 0.001M \] (Adjusted \( R^2=0.965 \) \hspace{1cm} Eq. (2)
where ‘k’ was the thermal conductivity (Wm⁻¹K⁻¹), ‘F’ was the fat content (% w.b.) and ‘M’ was the moisture content (% d.b.). A better and elaborative model was developed (Eq. 3) by considering the core temperature of pantoa, oil temperature, fat and moisture contents.

\[
k = 0.324 + 0.002M - 0.001CT - 0.001OT \quad (\text{Adjusted } R^2 = 0.981; R^2 = 0.983)
\]  

where ‘k’ was the thermal conductivity (Wm⁻¹K⁻¹), ‘M’ was the moisture content (% d.b.) and ‘CT’ and ‘OT’ were the core and oil temperatures, respectively. Among all the factors, moisture content of the product had the strongest influence on ‘k’ value.

It is well-known that the thermal conductivity of water is the highest among all food constituents such as fat, protein, carbohydrate and ash while that of fat is the lowest. The thermal conductivity of water is nearly 4 times as that of fat at the same temperature (Choi and Okos, 1986; Rahman, 1995). There was negative correlation between thermal conductivity and fat content. This could be the reason for decrease in thermal conductivity of pantoa during DFF.

**Thermal diffusivity (α)**

The thermal diffusivity of pantoa determined at different frying time-temperatures is illustrated in Fig. 3. The thermal diffusivity of pantoa increased as frying temperature increased. Thermal

![Fig. 2 Changes in thermal conductivity of pantoa at different frying conditions](image1)

![Fig. 3 Changes in thermal diffusivity of pantoa at different frying conditions](image2)
diffusivity increased from the initial value of 0.105 mm$^2$s$^{-1}$ to 0.120, 0.140 and 0.134 mm$^2$s$^{-1}$ up to 300 s, respectively at 125, 135 and 145ºC (Fig. 3). Thereafter, it decreased gradually till the end of frying regardless of the temperature. The changes in thermal diffusivity followed second order polynomial equation with $R^2=0.82$ at 125ºC, $R^2=0.72$ at 1235ºC and $R^2=0.77$ at 145ºC and mean RMSE value of 0.008. These results were coherent to the results of Vélez-Ruiz et al. (2002) during frying of chicken slabs at 130-150ºC. However, in the case of donuts, an increase in the ‘α’ value with frying temperature up to 120 s of frying was reported (Vélez-Ruiz and Sosa-Morales, 2003). The average ‘α’ values of pantoa were in the range observed during frying of pastry at 150ºC (0.102-0.156 mm$^2$s$^{-1}$) as reported by Williams and Mittal (1999).

Andersland and Anderson (1978) postulated that product with high thermal diffusivity experienced an increase in temperature faster than that of with low thermal diffusivity.

**Volumetric specific heat ($C_p$)**

The volumetric specific heat of pantoa samples measured at different frying temperature and time combinations is depicted in Fig. 4. The volumetric specific heat decreased to 1.607, 1.530 and 1.401 MJm$^{-3}$K$^{-1}$ from the initial value of 3.282 MJm$^{-3}$K$^{-1}$ at 125, 135 and 145ºC, respectively. Also, the ‘$C_p$’ value decreased with frying temperature as reported by Vélez-Ruiz and Sosa-Morales (2003) for donuts. In general, $C_p$ showed a trend similar to that of thermal conductivity. The decrease in $C_p$ value with time was attributed to the fall in moistness of fried pantoa. In contradiction to that Baik and Mittal (2003) reported that the specific heat of tofu increased with increase in temperature. As tofu was heated, the mean kinetic energy of the molecules present also increased. This in turn increased the collisions between molecules which imparted energy for their rotation. Rotation of molecules in turn increased the internal energy thereby, increasing the specific heat. However, the moisture content of tofu had higher effect on $C_p$ than temperature. The $C_p$ of pantoa samples fried at all temperatures was modeled using multiple linear regression analysis incorporating frying time, frying temperature, moisture content and fat content as independent factors. Since the temperature effect was insignificant, it was excluded from the model (Eq. 4), and the final model is shown below.

$$C_p = 10.967 - 0.2605F - 0.032M - 0.001t$$

(Adjusted $R^2=0.921$)  Eq. (4)

where $C_p$ was the volumetric specific heat (MJm$^{-3}$K$^{-1}$), ‘F’ was the fat content (% w.b.), ‘M’ was the moisture content (% d.b.) and ‘t’ was the frying time (s). A better and elaborative model was developed (Eq. 5) by considering the core temperature of pantoa, oil temperature, fat and moisture contents.

$$C_p = 6.017 - 0.011CT - 0.115F$$

(Adjusted $R^2=0.941$; $R^2=0.945$)  Eq. (5)

where $C_p$ was the volumetric specific heat (MJm$^{-3}$K$^{-1}$), ‘F’ was the fat content (% w.b.) and ‘CT’ was the core temperature. Amongst the factors, fat content was found to have a profound effect on the $C_p$ of pantoa.

A relatively high specific heat of water could be reason for high specific heat of pantoa dough due to the presence of moisture (Mohsenin, 1980). A negative relationship was found between fat content and volumetric specific heat of pantoa.

**Conclusions**

Thermal properties of pantoa during DFF were determined. Both thermal conductivity and volumetric specific heat decreased with respect to the frying temperature and time, whereas the thermal diffusivity increased with increase in frying temperature up to
270 s, 270 s and 240 s at 125, 135 and 145 °C, respectively and then decreased gradually with respect to frying time. The thermal conductivity, thermal diffusivity and volumetric specific heat varied from 0.357 to 0.199 Wm⁻¹K⁻¹, 0.105×10⁻⁶ to 0.140×10⁻⁶ m²s⁻¹ and 3.275 to 1.401 MJm⁻¹K⁻¹, respectively. Moisture content and fat content were inversely proportional during frying. Empirical models were developed for thermal conductivity and volumetric specific heat as function of moisture content, fat content and temperature. The thermal properties and the developed models would be useful in the mathematical modeling of heat transfer in pantoa during DFF.

Acknowledgments

The authors would like to express their sincere thanks to Mr. Ravinder Singh, Technical Assistant of Southern Regional Station of ICAR - National Dairy Research Institute, Bengaluru for his assistance in this project work.

References

Andersland OB, Anderson DM (1978) Geotechnical Engineering for Cold Regions, McGraw-Hill Inc., New York
AOAC (2000) Official Methods of Analysis of AOAC International. Washington DC
Ateba P, Mittal GS (1994) Modelling the deep-fat frying of beef meatballs. Int J Food Sci Tech 29: 429-440
Baik OD, Mittal GS (2003) Determination and modeling of thermal properties of tofu. Int J Food Prop 6: 9-24
BIS: (1981) ISI Handbook of Food Analysis. Part XI: Dairy Products. (SP:18). Bureau of Indian Standards, New Delhi, India
Budžaki S, Šeruga B (2005) Moisture loss and oil uptake during deep fat frying of “Krostula” dough. Eur Food Res Technol 220: 90-95
Choi Y, Okos MR (1986) Thermal Properties of Foods – Review. In: Physical and chemical properties of foods. Okos MR (Ed). St Joseph, MI: ASAE
Dincer I, Yildiz M (1996) Modelling of the thermal and moisture diffusion in cylindrically shaped sausages during frying. J Food Eng 28: 35-44
Gamble MH, Rice P, Selman JD (1987) Relationship between oil uptake and moisture loss during frying of potato slices from c.v. Record U.K. tubers. Int J Food Sci Technol 22: 233-241
Garayo J, Moreira RG (2002) Vacuum frying of potato chips. J Food Eng 55: 181-191.
Heldman DR, Lund DB (1992) Food freezing. In: Handbook of Food Engineering. Heldman DR, Lund DB (Eds). Marcel Dekker, New York
Jayakumar DR (1998) Development of probes for determination of thermal conductivity of some selected indigenous dairy products. M.Tech. Thesis. National Dairy Research Institute (Deemed University), Karnal, India
Mohsenin NN (1980) Physical Properties of Plant and Animal Materials Structure, Physical Characteristics and Mechanical Properties. Gordon and Breach Science Publishers, New York
Moreira RG, Palau J, Sun X (1995a) Simultaneous heat and mass transfer during the deep fat frying of tortilla chips. J Food Process Eng 18: 307-320
Moreira RG, Palau J, Sweat VE, Sun X (1995b) Thermal and physical properties of tortilla chips as a function of frying time. J Food Process Pres 19: 175-189
Neethu KC, Franklin MEE, Pushpadas HA, Menon RR, Rao KJ, Nath BS (2015) Analysis of transient heat and mass transfer during deep-fat frying of pantoa. J Food Process Pres 39: 966-977
Nayak AK, Sawhney IK (2004) Thermal conductivity of chhana measurement and correlations. Ind J Dairy Sci 57: 241-245
Nema PK, Prasad S (2004) Effects of frying temperature on quality and yield of potato chips. J Food Sci Technol 41: 448-450
Ngadi MO, Mallikarjunan P, Chinnan MS, Radhakrishnan S, Hung YC (2000) Thermal properties of shrimps, French toasts and breading. J Food Process Eng 23: 73-87
Rahman MS (1995) Food Properties Handbook. CRC Press, New York
Rajorhia GS, Srinivasan MR (1979) Technology of khoa- A review. Ind J Dairy Sci 32: 209-216
Rice P, Gamble MH (1989) Modelling moisture loss during potato slice frying. Int J Food Sci Technol 24: 183-187
Sahin S, Sastry SK, Bayindirli L (1999) Effective thermal conductivity of potato during frying: Measurement and modeling. Int J Food Prop 2: 151-161
Shih FF, Daigle KW, Glawson EL (2001) Development of low uptake donuts. J Food Sci 66: 141-144
Sweat VE (1975) Modeling the thermal conductivity of meats. Trans ASAE 18: 564-568
Tan KJ, Mittal GS (2006) Physicochemical properties changes of donuts during vacuum frying. Int J Food Prop 9: 85-98
Tungsangprateep S, Jindal VK (2004) Sorption isotherms and moisture diffusivity in fried cassava shrimp chips. Int J Food Prop 7: 215-227
Vélez-Ruiz JF, Sosa-Morales ME (2003) Evaluation of physical properties of dough of donuts during deep fat frying at different temperatures. Int J Food Prop 6: 341-353
Vélez-Ruiz JF, Vergara-Balderas FT, Sosa-Morales ME, Xique-Hernandez J (2002) Effect of temperature on the physical properties of chicken strips during deep-fat frying. Int J Food Prop 5: 127-144
Kumari A, Emerald FME, Simha V, Pushpadas HA (2015) Effects of baking conditions on colour, texture and crumb grain characteristics of chhana podo. Int J Dairy Technol 68: 270-280
Williams R, Mittal GS (1999) Low-fat fried foods with edible coatings: Modeling and simulation. J Food Sci 64: 317-322