Analysis of modes of heat transfer in baking Indian rice pan cake (*Dosa*,) a breakfast food

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Abstract Heat transfer by individual modes is estimated during baking of rice (*Oryza sativa*) pan cake (*Dosa*), a traditional food. The mathematical expressions proposed could be used to modify the baking oven for controlling the individual modes of heat transfer to obtain the desired product texture, colour and flavour. Conduction from the rotating hot plate is found to be the most prominent mode of heat transfer and is critical for obtaining the desired product characteristics such as texture and flavour. Temperature profiles along the thickness of *Dosa* are obtained and compared with those obtained experimentally. Heat transfer parameters such as thermal conductivity and emissivity of *Dosa* are determined (0.42 W/m K and 0.31, respectively). The effect of material of construction of the hot plate such as alloy steel, teflon coated aluminum, cast iron and stainless steel on product texture was studied and stainless steel was found to give good surface finish to the product, which was confirmed by scanning electron microscope. Sensory evaluation was carried out to evaluate the product acceptability. The thermal efficiency of the baking oven was 51.5%.

Keywords Indian rice pan cake (*Dosa*) · Modes of heat transfer · Thermal conductivity · Emissivity · Temperature profiles · Energy balance

Introduction

Indian traditional foods based on different cereals/grains are popular for their unique taste and flavor (Sarojini et al. 1996a, b; Roopa et al. 1998; Tripathy et al. 2003). Indian rice pan cake (*Dosa*) is one of the most popular traditional foods. *Dosa* is a breakfast food made from the batter of ground rice, blackgram/*dhal* and water, which is allowed to ferment (Vasan and Kousalya 1982; Patil et al. 2001) for about 15–17 h at a temperature between 313–318 K.

In case of a conventional *Dosa*, hot plate (*tava*) is used domestically for baking and the *tava* is heated at the bottom by any of the heat sources such as firewood, charcoal, coal, kerosene or liquefied petroleum gas (LPG). Conduction from hot plate and radiation from the hood/top cover are considered most important for the desired product quality. It is a general feeling that heat transfer by radiation significantly contributes for baking of *Dosa*. One of the objectives of the study was to verify how far this is true.

The process of bread preparation has been studied for its attributes by Adler (1958). Role of individual modes of heat transfer for baking of biscuits has been reported by Standing (1974) using band oven. Importance of quality of wheat flour for preparation of chapathi an Indian traditional food has been studied (Chaudhri and Muller 1970). Tandoori roti, a popular Indian traditional product is baked using a Tandoor oven, which is an in ground oven consisting an earthen pot surrounded by bricks. The analysis of modes of heat transfer in Tandoor oven has been reported (Saxena et al. 1995).

In all these studies, it was acknowledged that the mode of heat transfer is more important than just supplying the required quantity of heat for obtaining the desired product characteristics such as flavor, crustiness and color. Hence, it was thought desirable to analyze the effect of individual

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modes of heat transfer in baking of *Dosa* on these characteristics. Rheological properties of the *Dosa* batter was studied by Bhattacharya and Bhat (1997) which is important for batter standardization. A mathematical expression developed to analyze the contributions of the individual modes of heat transfer, which is expected to be useful in improving the *Dosa* characteristics as well as in modifying the design of the baking oven. The study also includes the analysis of the temperature profiles (experimental and theoretical) along the thickness of *Dosa*. The experiments were also conducted with different hot plate materials (*tava*) such as alloy steel, teflon coated aluminum, cast iron and stainless steel to study its effect on texture of *Dosa*. The product was examined under a scanning electron microscope to understand the structural changes and the crater density is attributed to the surface finish of *Dosa*. A sensory analysis was carried out from the trained panelists to evaluate *Dosa* made from baking oven.

Theoretical aspects

Considering the baking of *Dosa* made from rice and blackgram batter spread on a rotating hot plate (*tava*), the main mechanisms of heat transfer to the product are conduction from the rotating hot plate and radiation from the hood. Convection heat transfer is not considered, as the air/flue gas flow is very less. Thus total heat transferred to *Dosa* (Q_T) can be written using expressions given elsewhere (Kern 1950; McCabe et al. 1995; Heldman and Singh 1993) as,

$$Q_T = q_C + q_R \\ = K A_b (T_{pb} - T_{pt})/x + F_{pr} A_b \sigma (T_H^4 - T_{pt}^4) \quad (1)$$

Where,

$$F_{pr} = 1/\{1/f_{pr} + (1/\varepsilon_p - 1) + (A_b/A_r)(1/\varepsilon_H - 1)\} \quad (2)$$

and q_C is heat transferred by conduction, kJ; K is the thermal conductivity of *Dosa*, W/m K; A_b the area of the product bottom in contact with the hot plate, m^2 ; T_{pb} *Dosa* bottom surface temperature which is in equilibrium with the hot plate temperature and equal to it K; T_{pt} the temperature of *Dosa* top surface at the end of the baking period, K and x the thickness of *Dosa*, m. q_R is the heat transferred by radiation, kJ; σ the Stefan-Boltzman constant, $W/m^2 h K^4$; T_H the hood (refractory surface) temperature, K, F_{pr} overall coefficient for radiation heat transfer (Charm 1975; Heldman and Singh 1993), f_{pr} is geometrical factor; ε_p the emissivity of *Dosa*; ε_H emissivity of the hood and A_r area of the radiating refractory surface, m^2 .

The total heat transferred must be equal to the total heat absorbed by *Dosa*. Considering the gross temperature rise of *Dosa* (sensible heat increase) and the latent heat of vaporization of evaporated moisture, the total theoretical heat absorbed (Q_A) can be expressed as,

$$Q_A = \{mC_p(T_{pt} - T_d)\}/t + \{L\lambda_v\}/t \quad (3)$$

where, m is average mass of *Dosa*—batter, kg; C_p average heat capacity, kJ/kg K; T_d the *Dosa*—batter temperature at the beginning of the baking period, K; t the *Dosa* baking time, s; L the moisture loss during baking, kg; T_{pt} the temperature of the product top surface at the end of the baking period, K and λ_v latent heat of water evaporation, kJ/kg.

It would be of interest to obtain the temperature profiles across the thickness of the product. The time-temperature-distance relationship for the body of uniform temperature subject to sudden source of heat can be represented by the most general equation of this type (Perry and Green 1984).

$$T = C_1 + C_2x + C_3e^{-pt} e^{qx} \quad (4)$$

where, T is the temperature of product K; C_1 , C_2 , C_3 , p and q are constants. The initial and boundary conditions for the present case (an infinite slab heated on one face) are,

$$t = 0; x = x, T = T_d \\ x = 0, t = 0, T = C_1 = T_s = T_{pb}$$

where, T_s is the hot plate temperature, K.

$$T_{t=0} = T_{pb} = C_1 + C_2x + C_3 = T_d$$

The above equation is valid only when, $C_2=0$, otherwise T_d would have to vary with x , whereas it is assumed to be uniform. Hence,

$$T_{t=0} = C_1 + C_3 = T_d \text{ or } C_3 = T_d - T_{pb}.$$

Substituting in Eq. 4, results in

$$T = T_p + (T_d - T_p)f_1(x/2\sqrt{\alpha t}) \quad (5)$$

where, $f_1(x/2\sqrt{\alpha t})$ denotes the error integral and α thermal diffusivity, m^2/s . For different values of x , α and t , the factor $(x/2\sqrt{\alpha t})$ was calculated to obtain the corresponding error integral. The values of the integral are obtained from literature (Perry and Green 1984).

Material and methods

Baking oven The baking oven employed in the present study was designed and developed at the Institute (Venkateshmurthy and Jayaprakashan 2000, 2002). The cross sectional view of the automatic *Dosa* machine is shown in

Fig. 1 Automatic pan cake (*Dosa*) machine

Fig. 1. The baking oven consists of a geared motor, a spreader assembly and a revolving hot plate (hot plate rotates at 0.5 rpm having thermal conductivity of 54 W/m K) assembly. A circular burner with accessories is used for heating the hot plate and heating is from the bottom of the hot plate (hot plate has a diameter of 1.2 m and thickness of 0.12 m) and a scraper is used for scraping of *Dosa* from the hot plate. The main frame with necessary insulation houses all the parts of the machine and batter pump attached to a vessel is coupled to a solenoid valve. A set of sprocket assembly is used for the drive of the hot plate and the end of the main drive is housed inside anti-friction bearings. An electronic timer controls the volume of the batter and the temperature of the hot plate is controlled by a temperature controller. All the electrical parts of the machine are housed inside an electrical panel board. The whole assembly is mounted on swivel castors for easy movement of the device to the required place. The baking oven has a capacity to produce 360 *Dosas*/h. At any given time there will be around 12 *Dosas* on the hot plate of the baking oven.

Preparation of Dosa Batter was prepared by grinding soaked rice (*Oryza sativa*) and *urd dhal*/blackgram dhal

(*Phaseolus mungo*) with water in known proportions (4:1:5) for a predetermined time to get the required fineness. The batter was allowed for auto fermentation for 15–17 h. The *Dosa* batter was charged (0.1 kg/*Dosa* or 100 ml/*Dosa*) to a batter dispenser and on to the preheated rotating hot plate (443~453 K) of the baking oven and the batter was spread to a size of 0.2~0.23 m in diameter with a thickness of 0.002~0.004 m or 2~4 mm by a spreader and oil was sprayed (0.008~0.010 kg/*Dosa* or 8~10 g/*Dosa*) on to the product which will not only improve the sensory properties of the product but also aid in rapid and uniform heat transfer. The baked products were scraped and discharged for consumption. The average baking time of the product was about 120 s. The average value of the moisture content of the batter and the baked product were 65 and 35%, respectively.

Determination of thermal conductivity (K) Dosa was baked on the hot plate by discharging a known amount of batter of predetermined composition as described above. The top of the product was covered by an asbestos plate of 0.005 m or 5 mm thickness to prevent radiation from the stainless steel hood and to allow the product baking by conduction alone. The probe of

Table 1 Thermal conductivity (K) as a function of hot plate temperature

Trial No.	Hot plate temp K	Total heat W		Final temp. of <i>Dosa</i> K	Mass of batter kg (Initial)	Mass of <i>Dosa</i> kg (Final)	Thermal conductivity W/m. K
	(T_s)	(Q_A)		(T_{pt})	(m)	(m_I)	(K)
		Sensible Heat, (Q_2)	Latent heat, (Q_3)				
1	458.00	192.31	532.29	353.50	0.1	0.072	0.44
2	443.50	188.84	451.33	347.60	0.1	0.076	0.43
3	445.00	191.58	459.79	348.50	0.1	0.076	0.40

Table 2 Emissivity of rice pan cake (*Dosa*) (ε_p) as a function of refractory surface temperature

Trial No.	Hood temp K (T_H)	Final temp. of <i>Dosa</i> K (T_{pt})	Mass of batter kg (Initial) (m)	Mass of <i>Dosa</i> kg (Final) (m_f)	Emissivity of <i>Dosa</i> (ε_p)
1	414.0	313.5	0.1	0.103	0.29
2	433.3	323.2	0.1	0.093	0.31
3	440.0	330.6	0.1	0.092	0.33

the temperature indicator was positioned through a hole at the center of asbestos disc to measure the product surface temperature. Thermal conductivity was calculated from these test results by using appropriate terms in Eqs. 1 and 3.

Determination of product emissivity (ε_p) *Dosa* batter was spread on the asbestos sheet and placed on to the hot plate with another asbestos insulation at the bottom (to avoid conduction heat transfer). The batter was baked by radiation alone from the hood of the machine. The temperature of the hood was recorded. Emissivity was calculated from these test results by using appropriate terms in Eqs. 1 and 3.

Determination of the temperature profiles (T) The uniform thickness of *Dosa* batter was spread on to the hot plate, which was maintained at uniform temperature. A cylinder with a hole for insertion of the thermocouple was used for measuring the temperature at different depths of the *Dosa*. Thickness gauge having thickness varying from 0.0005 to 0.002 m or 0.5 to 2 mm was used for varying the depth of insertion of the thermocouple for measuring the temperature at different depths/thickness of *Dosa*. A digital temperature

indicator (Model–TFF 200, Make–EBRO, Germany, PT-100, Range: –50 to 200 °C) was employed to measure the product temperature and had a resolution of 0.1 °C. Increase in temperature of the product batter was recorded at different time intervals from 30–120 s at different depths.

Determination of microstructure *Dosa* was prepared using hot plates of different material such as cast iron, stainless steel, steel and teflon coated aluminum. The *Dosa* samples prepared on different hot plate materials (*tava*) were viewed under the scanning electron microscope (model-Leo 435VP of Leo Electron Microscope Ltd., Cambridge, UK) at a magnification of 500. The thermal conductivity of the different hot plate materials was in the range of 16–54 W/m K.

Sensory analysis *Dosa* was prepared on the baking oven of the automatic *Dosa* machine. Sensory characteristics of the product were tested among 10 panelists using quantitative descriptive analysis (Stone et al. 1974).

Results and discussion

In order to test the exclusive effect of conductive heat transfer, *Dosa* was heated from the bottom only (while preventing radiation by covering the product with an asbestos disc) on the hot plate of the baking oven at three different preset temperatures. Thermal conductivity of product was calculated by setting the total heat absorbed by the product equal to the expression for conduction. The results of these experiments are given in Table 1 and the average thermal conductivity of the product was found to be 0.42 W/m K.

Fig. 2 Temperature profiles across the thickness of rice pan cake (*Dosa*) (Experimental/Theoretical)

Fig. 3 Microstructure of rice pan cake (*Dosa*) made on different hot plate material

The expressions for radiation from hood/cover surfaces given in equations are simplified by assuming the value of both hood/cover emissivity (ε_H) and the geometric factor (f_{pr}) to be unity, which are valid assumptions under the conditions of the present investigation, as

$$q_R = \varepsilon_p \cdot A_b \cdot \sigma \cdot (T_H^4 - T_{pt}^4) \quad (6)$$

When the product was baked only through radiation heat, as described earlier, there was no appreciable change on the product surface (except for the formation of a thin hard layer). The characteristic holes on the top of the product were also absent. This could be attributed to the fact that the product was not being in contact with the surface of the hot plate, indicating the importance of

conduction heating in baking of product. The result of test runs is given in Table 2. Using Eq. 3, the total theoretical heat absorbed by the test product was calculated using temperature and moisture data given in Table 1. The value of specific heat (C_p) is taken as 1.83 kJ/kg for computing the sensible heat requirement of the product (Gupta 1990). The emissivity of the product surface (ε_p) calculated by setting the total theoretical heat absorbed by the product equal to the expression for emissivity in Eq. 6, was found to be 0.31. This value was used in subsequent calculations. Equation 6 can be written as,

$$Q_R = 0.31 A_b \sigma (T_H^4 - T_{pt}^4) \quad (7)$$

Fig. 4 Profilogram of product made using automatic *Dosa* machine ($n=15$ panelists)

The complete heat transfer model as expressed by Eqs. 1 and 3 was then applied to the baking in the baking oven. The total heat absorbed [Eq. 3] was taken as a sum of latent heat and sensible heat. On conducting several experiments each term of Eq. 1 was calculated for this purpose. It can be noted that approximately 532 W of the heat absorbed by the product was latent heat of evaporation (Q_3) of water while sensible heat (Q_2) was about 192 W. It is interesting to note that, of the total heat transferred (Q_T) to the product, about 98% was transferred by conduction from the rotating hot plate and about 1.5% was transferred by radiation from the hood/cover. The heat transfer distribution clearly indicates the significant contribution from conduction, which was crucial for the characteristic flavor and crustiness of the *Dosa*. Thermal efficiency of the baking oven was found to be about 51%.

The temperatures across the thickness of the product were estimated using the Eq. 5. The temperature profiles, both experimental and theoretical are shown in Fig. 2 and it may be noted that the trend of these profiles are similar. However, the experimental temperatures are much lower than the theoretical ones. The reduction in the temperatures of the experimental value could be attributed to the evaporative cooling that occurs during baking of *Dosa*.

Dosa was prepared using different hot plate material such as cast iron, stainless steel, steel and Teflon coated aluminum. The product was viewed under the scanning electron microscope to see the pattern of craters formed due to the evaporation of moisture during the baking process. It was clearly seen from the Fig. 3 that, material such as stainless steel and teflon coated aluminum had smaller and uniform craters of large numbers as compared to the cast iron and alloy steel material. This can be attributed to the fact that the material with lower thermal conductivity has uniform distribution of heat and also lower rate of heat transfer compared to alloy steel and cast iron. The difference in density of the craters was clearly seen in better surface finish of the product prepared using stainless steel and teflon coated aluminum hot plate materials.

The sensory analysis was carried out among the 10 panelists using quantitative descriptive analysis. The profilegram (Fig. 4) indicated high overall acceptability of *Dosa* by the panelists (scored 11 out of 15).

Conclusion

In baking of *Dosa* made from rice and blackgram batter conduction heat transfer is found to play the most prominent role in determining its characteristic flavour and texture. Hence, the amount of heat supplied by

individual modes of heat transfer is to be controlled rather than the total heat supplied to the product in order to achieve the desired product characteristics. The mathematical expressions are of significant use in estimating the magnitude of the heat transfer and contribution from each individual heat transfer modes, which in turn is useful for design modifications of the burner of the hot plate of the baking oven. The experimental temperature profiles across the thickness of the product indicated similar trend of the theoretical ones, however, the values are lower than the theoretical ones which could be attributed to evaporative cooling that takes place during baking of *Dosa*. The sensory analysis indicated a reasonably good over all quality of the product baked on the baking oven.

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