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The effect of open sun and indoor forced convection on heat transfer coefficients for the drying of papad

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Abstract
In this research paper, a simulation study has been carried out for the determination of convective heat transfer coefficients of papad under open sun drying and indoor forced convection drying modes. Experimental data obtained from open sun and indoor forced convection drying modes for papad were used to determine the values of the constants (C and n) in Nusselt number expression by using linear regression analysis, and consequently convective heat transfer coefficients were evaluated. The average values of convective heat transfer coefficients were found to be 3.54 and 1.56 W/m^2 °C under open sun drying and indoor forced convection drying modes respectively. The experimental errors in terms of percent uncertainty were also evaluated.

Keywords: papad, convective heat transfer coefficient, open sun drying, forced convection drying

Nomenclature

d	diameter of the wire mesh tray, m
A_t	area of circular wire mesh tray, m^2
C	constant
C_v	specific heat of humid air, J/kg °C
g	acceleration due to gravity, m/s^2
Gr	Grashof number
h_c	convective heat transfer coefficient, W/m^2 °C
$h_{c,av}$	average convective heat transfer coefficient, W/m^2 °C
K_v	thermal conductivity of humid air, W/m °C
m_{ev}	moisture evaporated, kg
n	constant
Nu	Nusselt number = $h_c X / K_v$
Pr	Prandtl number = $\mu_v C_v / K_v$
Re	Reynolds number = $\rho_v V d / \mu_v$
$P(T)$	partial vapour pressure at temperature T, N/m^2
Q_e	rate of heat utilized to evaporate moisture, J/m^2 s
t	time, s
T_p	papad surface temperature, °C
T_e	temperature just above papad surface in open sun drying and exit air temperature during forced mode, °C
$\bar{T}_p$	average papad surface temperature, °C
$\bar{T}_e$	average temperature of humid air, °C
T_i	average of papad surface and humid air tem perature, °C
ΔT	effective temperature difference, °C
X	characteristic dimension, m
V	air velocity, m/s

Greek symbols

β	coefficient of volumetric expansion, 1/ °C
γ	relative humidity, %
$\bar{\gamma}$	average relative humidity, %
λ	latent heat of vaporization, J/kg
μ_v	dynamic viscosity of humid air, kg/m.s
r_v	density of humid air, kg/m^3

1 Introduction

Papad is an indigenous savoury food item consumed in most Indian homes. Generally, it is prepared in households by rolling dough consisting of flour of different pulses containing water content varying from 27-30% per kg of papad weight. It is made into a circular shape with thickness generally varied from 0.3 to 2 mm and is dried by different means to a moisture level of 14–15% (Math *et al.,* 2004). Open sun drying is one of the most primitive methods of papad drying and it is still practised in India despite many disadvantages associated with it. Papad drying involves a heat and mass transfer phenomenon in which heat energy supplied to the papad surface is utilized in two ways: (i) to increase the papad surface temperature in the form of sensible heat and (ii) to vaporize the moisture present in papad through provision of the latent heat of vaporization. The removal of moisture from the interior of the papad takes place due to induced vapour pressure difference between the papad and surrounding medium. The moisture from the interior diffuses to the papad surface to replenish the evaporated surface moisture.

The convective heat transfer coefficient is an important parameter in drying rate simulation since the temperature difference between the air and papad varies with this coefficient. Sodha *et al.* (1985) presented a simple analytical model based on simultaneous heat and mass transfer at the product surface and included the effect of wind speed, relative humidity, product thickness, and heat conducted to the ground for open sun drying and for a cabinet dryer. Some theoretical and experimental studies on drying have been reported by Garg (1987). Sokhansanj (1987) used experimental data for thin layer drying of barley to show that a model of coupled heat and mass transfer within a single kernel of grain improves prediction of the drying rate. Miketinac *et al.* (1992) studied the drying of a thin layer of barley and formulated five models simulating the process of simultaneous heat and mass transfer. Depending upon the form of a drying model the heat transfer coefficient was found to vary between 43 and 59 W/m^2 °C. Goyal and Tiwari (1998) have studied heat and mass transfer in product drying systems and have reported the values of a convective heat transfer coefficient for wheat and gram as 12.68 and 9.62 W/m^2 °C, respectively, by using the simple regression and 9.67 and 10.85 W/m^2 °C respectively, for the same products while using the multiple regression technique. The convective heat transfer coefficients for some crops (green chillies, green peas, white gram, onion flakes, potato slices and cauliflower) under open sun drying were reported by Anwar and Tiwari, (2001a). The values of convective heat transfer coefficients were found to vary from 3.71-25.98 W/m^2°C. Togrul (2003) has determined the convective heat transfer coefficients of some crops dried under open sun conditions which were found to vary with a range of 0.768 to 3.292 W/m^2 °C. Akpinar (2004) determined the convective heat transfer coefficient of various agricultural products, namely, mulberry, strawberry, apple, garlic, potato, pumpkin, eggplant, and onion under open sun drying. The convective heat transfer coefficient of these crops was found to vary from crop to crop with a range of 1.136-11.323 W/m^2°C. Togrul (2005) determined the convective heat transfer coefficient of apricots in open sun drying conditions which were found to vary from 0.0374 to 2.046 W/m^2°C. Anwar and Tiwari (2001b) determined the convective heat transfer coefficients of various agricultural crops under forced convection drying which were found to vary within a range between 1.31 and 12.80 W/m^2°C. A number of researchers on papad have also been carried out by various workers considering its diametrical expansion, water and oil absorption etc. (Bhattacharya and Narasimha, 1999; Velu *et al*., 2004; Math *et al.,* 2004).

In this research paper, the convective heat transfer coefficients have been found by determining the values of the constants (C and n) in the Nusselt number expression for papad drying under open sun and indoor forced convection drying modes. These values would be helpful in designing a dryer for dry papad to its optimum storage moisture level of 15%.

2 Experimental set-up and procedure

A circular shaped wire mesh tray of diameter 0.18 m was used to accommodate the papad. A digital weighing balance (Scaletech, model TJ-6000) of 6 kg capacity having a least count of 0.1 g was used to measure the mass of moisture evaporated. A non-contact (infra-red thermometer) thermometer (Raytek-MT4) having a least count of 0.2 °C with an accuracy of ± 2% on a full scale range of -1 to 400 °C was used to measure the temperature of the papad surface. A six channel digital temperature indicator (0 to 300°C, least count of 0.1 °C) with a calibrated copper-constantan thermocouple was used to measure the ambient temperature. A digital hygrometer (model Lutron-HT3006HA) was used to measure the relative humidity and temperature of air (just above the papad surface in case of open sun drying mode and exit air in case of forced convection mode). A heat convector (Usha Shriram, model FH-812T, 230V, a.c., two heating coils of 1000W each and air speed of 0.4 m/s) was used to blow hot air of 80 °C over the papad surface during the forced convection mode.

Experiments were conducted in the month of April 2008 for both the natural and forced convection mode in the climatic conditions of Hisar (29°5'5" N 75°45'55" E). The papad was kept on the weighing balance using the wire mesh tray. A digital hygrometer was kept just above the papad surface with its probe facing downwards towards the papad surface to measure the humidity and temperature of the air. Every time, it was kept on 2 minute before recording observations. All the observations were recorded at every 5 minute time intervals. The whole unit was kept in open sun at a place with negligible wind velocity. The difference in weight directly gave the quantity of water evaporated during that time interval. The photograph of the experimental set-up under open sun drying is shown in Figure 1.

Under the forced convection mode as shown in Figure 2, a heat convector was used to blow the hot air over the surface of the papad. A digital hygrometer was used for measuring the relative humidity and temperature of the exit air. It was kept after the papad tray, keeping its probe facing the exit air. Observations were recorded for papad surface temperature, exit air temperature, exit air relative humidity and papad weight at every 5 minute intervals. Average values of papad surface temperature ($\bar{T}_p$), exit air temperature ($\bar{T}_e$) and relative humidity ($\bar{\gamma}$) were calculated from two consecutive values for that time interval and were used in the calculations. The photograph of the experimental set-up for drying papad under forced convection mode is shown in Figure 2.

3 Sample preparation

Papad was freshly prepared by taking the flour of moong bean (Indian trade name – moong) and phaseolus mungo (Indian trade name – urad dal) mixed with 27.5% water content per kg of papad weight. The flour was purchased locally, and that fraction of flour which passed through an eighty five mesh (180 microns) British Standard sieve was used for making papad. Dough was made and rolled in a circular shape of 0.65-0.80 mm thickness and 180 mm diameter with the help of pastry-board and pastry-roller.

A very little amount (two drops only; one drop each on the surface of a pastry board and the pastry roller) of mustard oil was applied on the surface of the pastry-board and pastry-roller so that papad does not stick to it during its rolling which is a general practice. The freshly prepared papad of 23.5 grams was used for both open sun drying and forced convection drying modes.

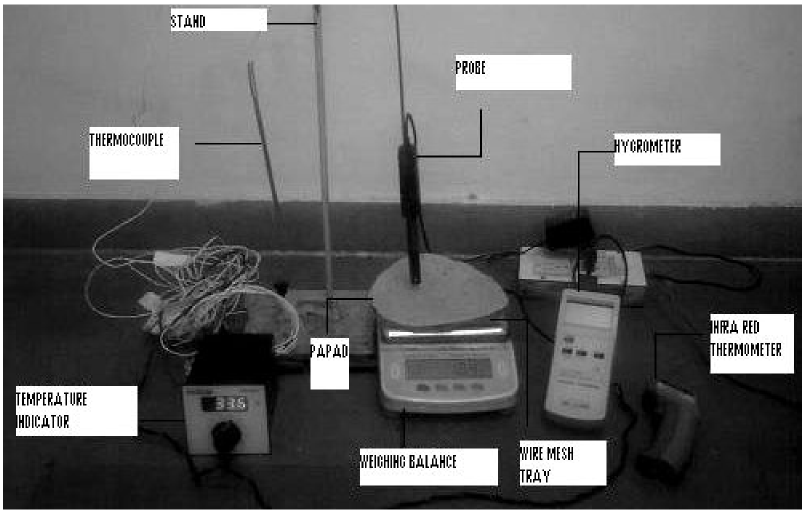

Figure 1: Experimental set-up for open sun drying mode

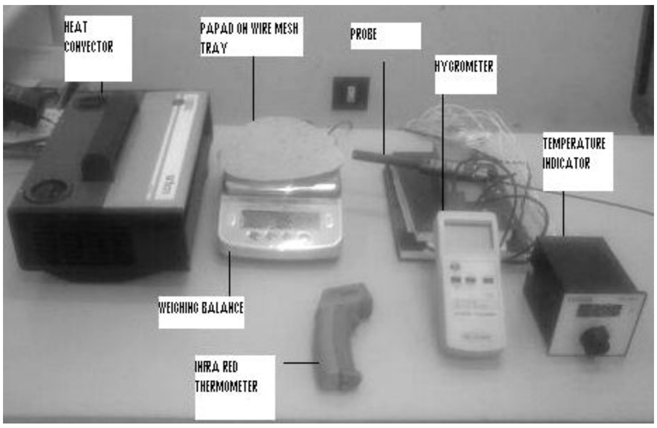

Figure 2: Experimental set-up for forced convection drying mode

Table 1: Observations for papad under open sun drying mode

Time	*W (gm)*	T_p (°C)	T_e (°C)	γ (%)	m_{ev}(gm)	$\bar{T}_p$ (°C)	$\bar{T}_e$ (°C)	$\bar{\gamma}$ (%)
10:00am	23.5	32.4	41.3	31.00	-	-	-	-
10:05am	22.0	33.8	37.8	32.60	1.5	33.1	39.55	31.80
10:10am	20.7	37.6	42.0	28.60	1.3	35.7	39.90	30.60
10:15am	19.8	42.6	45.1	27.30	0.9	40.1	43.55	27.95
10:20am	18.7	44.6	47.5	24.30	1.1	43.6	46.30	25.80
10:25am	17.6	47.0	49.0	22.20	1.1	45.8	48.25	23.25
10:30am	16.9	47.4	50.2	22.00	0.7	47.2	49.60	22.10
10:35am	15.9	48.8	46.9	24.20	1.0	48.1	48.55	23.10
10:40am	15.1	50.8	49.0	23.00	0.8	49.8	47.95	23.60

Table 2: Observations for papad under forced convection drying mode

Time	W (gm)	T_p (°C)	T_e (°C)	γ (%)	m_{ev}(gm)	$\bar{T}_p$ (°C)	$\bar{T}_e$ (°C)	$\bar{\gamma}$ (%)
2:05pm	22.1	45.2	66.6	14.3	-	-	-	-
2:10pm	19.8	52.0	71.8	12.8	2.3	48.60	69.2	13.55
2:15pm	18.6	55.8	73.2	12.4	1.2	53.90	72.5	12.60
2:20pm	17.2	58.2	73.3	11.7	1.4	57.00	73.25	12.05
2:25pm	16.2	59.2	73.6	11.5	1.0	58.70	73.45	11.60
2:30pm	15.0	60.8	76.6	10.5	1.2	60.00	75.10	11.00
2:35pm	13.9	61.8	77.2	10.8	1.1	61.30	76.90	10.65
2:40pm	12.9	62.4	78.4	10.6	1.0	62.10	77.80	10.70
2:45pm	12.0	63.0	80.3	10.4	0.9	62.70	79.35	10.50
2:50pm	11.2	63.4	80.3	10.4	0.8	63.20	80.30	10.40

4 Observations and thermal modelling

The values of observations recorded for open sun drying and forced convection drying modes are reported in Table 1 and Table 2 respectively.

The convective heat transfer coefficient can be calculated using the expression for Nusselt number as (Tiwari and Suneja, 1997):

$$Nu = \frac{h_c X}{K_v} = C(Gr\,\mathrm{Pr})^n \quad \text{(For open sun drying mode)}$$

and

$$Nu = \frac{h_c X}{K_v} = C(\mathrm{RePr})^n \quad \text{(For forced convection drying mode)}$$

or

$$h_c = \frac{K_v}{X} C(Gr\,\mathrm{Pr})^n \tag{1a}$$

$$h_c = \frac{K_v}{X} C(\mathrm{RePr})^n \tag{1b}$$

The rate of heat utilized to evaporate moisture is given as (Malik *et al.,* 1982)

$$Q_e = 0.016 h_c \left[P(T_p) - \gamma P(T_e)\right] \tag{2}$$

On substituting hc from equation (1a), equation (2) becomes

$$Q_e = 0.016 \frac{K_v}{X} C(Gr\,\mathrm{Pr})^n \left[P(T_p) - \gamma P(T_e)\right] \tag{3}$$

The moisture evaporated is determined by dividing equation (3) by the latent heat of vaporization (λ) and multiplying by the area of the tray (A_t) and time interval (*t*)

$$m_{ev} = \frac{Q_e}{\lambda} t A_t = 0.016 \frac{K_v}{X\lambda} C(Gr\,\mathrm{Pr})^n \left[P(T_p) - \gamma P(T_e)\right] t A_t \tag{4}$$

Let $0.016 \frac{K_v}{X\lambda} \left[P(T_p) - \gamma P(T_e)\right] t A_t = Z$

$$\frac{m_{ev}}{Z} = C(Gr\,\mathrm{Pr})^n \tag{5}$$

Taking logarithm on both sides of equation (5)

$$\ln\left[\frac{m_{ev}}{Z}\right] = \ln C + n \ln(Gr\,\mathrm{Pr}) \tag{6}$$

This is the form of a linear equation,

$$Y = mX_0 + C_0$$

Where

$$Y = \ln\left[\frac{m_{ev}}{Z}\right], \; m = n, \; X_0 = 1n(GrPr), \; C_0 = 1nC$$

Thus, $C = e^{C_0}$

Similarly in the case of forced convection mode

$$Y = \ln\left[\frac{m_{ev}}{Z}\right], \; m = n, \; X_0 = 1n(RePr), \; C_0 = 1nC$$

and $C = e^{C_0}$

By using the data of Tables 1 and 2, the values of Y and X_0were evaluated for different time intervals and then the constants C and n were obtained from the above equations. The values of constants C and n were further used to evaluate convective heat transfer coefficients from equations (1a) and (1b) under open sun drying and forced convection drying modes respectively. The physical properties of humid air, i.e., specific heat (C_v), thermal conductivity (K_v), density (ρ_v), viscosity (μ_v) and partial vapour pressure were calculated using the following expressions (Anwar and Tiwari 2001a):

$$C_v = 999.2 + 0.1434T_i + 1.101\times10^{-4}T_i^2 - 6.7581\times10^{-8}T_i^3 \quad (7)$$

$$K_v = 0.0244 + 0.7673\times10^{-4}T_i \quad (8)$$

$$\rho_v = \frac{353.44}{T_i + 273.15} \quad (9)$$

$$\mu_v = 1.718\times10^{-5} + 4.620\times10^{-8}T_i \quad (10)$$

$$P(T) = \exp\left[25.317 - \frac{5144}{(T + 273.15)}\right] \quad (11)$$

Where

$$T_i = \frac{\overline{T}_p + \overline{T}_e}{2}$$

5 Experimental results and discussion

The average of papad surface temperature ($\overline{T}_p$), exit air temperature ($\overline{T}_e$) and exit air relative humidity ($\overline{\gamma}$) were used to determine the physical properties of the humid air which were further used to calculate the values of Grashof number, Reynolds number and Prandtl number. The values of 'C' and 'n' in equation (1) were obtained by simple linear regression analysis, and, thus the values of hc were determined for both open sun drying and forced convection drying modes as tabulated in Table 3.

Table 3: Values of *C*, *n* and h_c under open sun drying and forced convection drying modes

C	n	h_c ($W/m^2\ ^oC$)	$h_{c,av}$ ($W/m^2\ ^oC$)
Open sun drying mode			
0.96	0.23	2.11-5.52	3.54
Forced convection drying mode			
0.99	0.29	1.54-1.56	1.56

The convective heat transfer coefficients variations with respect to time for open sun drying and forced convection drying modes are shown in Figure 3 and Figure 4 respectively. It could be seen from Figures 3 and 4 that mode of drying affects the convective heat transfer coefficients considerably and open sun drying gave the higher values. Further, the convective heat transfer coefficients for forced convection drying were observed almost constant.

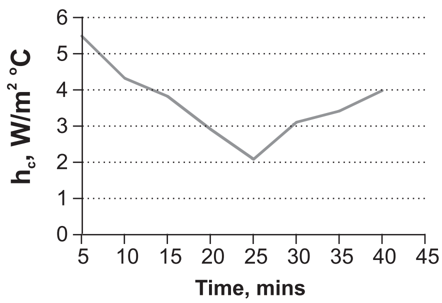

Figure 3: h_c vs time for papad under open sun drying mode

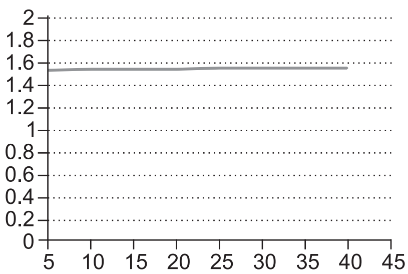

Figure 4: h_c vs time for papad under forced convection drying mode

The experimental method used is an indirect approach for determining the convective heat transfer coefficient based on the mass of moisture evaporated from the papad surface. This approach will certainly have a considerable degree of experimental uncertainty in the estimation of convective heat transfer coefficients. An estimate of internal uncertainty was carried out for experimental observations. External uncertainty has also been evaluated by taking into account the errors which occurred in taking the measurements for mass evaporated, temperatures and relative humidity which has been considered by taking the least count of the measuring instruments. The values of percent uncertainty (internal + external) were found to be 23.92% and 35.23% for papad under open sun drying and forced convection drying modes respectively which are reported in Table 4.

Table 4: Experimental percent uncertainties for papad

Drying mode	*Internal uncertainty (%)*	*External uncertainty (%)*	*Total uncertainty (%)*
Open sun drying	23.32	0.6	23.92%
Forced convection drying	34.63	0.6	35.23%

6 Conclusions

The convective heat transfer coefficients for papad under open sun drying and forced convection modes were determined using the values of the constants, 'C' and 'n' in the Nusselt number expression, obtained for papad based on experimental data by using the linear regression technique. The values of convective heat transfer coefficients under open sun drying and forced convection modes were found to be 3.54W/m^2 °C and 1.56 W/m^2 °C respectively. The experimental errors for open sun drying and forced convection were found to be 23.92% and 35.23% respectively.

Appendix

The following linear regression formulae were used to calculate C and n

$$n = \frac{N_o \sum X_0 Y - \sum X_0 \sum Y}{N_o \sum X_0^{\,2} - \left(\sum X_0\right)^2}$$

and

$$C_0 = \frac{\sum X_0^{\,2} \sum Y - \sum X_0 \sum X_0 Y}{N_o \sum X_0^{\,2} - \left(\sum X_0\right)^2}$$

The experimental error were also determined in terms of % uncertainty (internal + external).The following equations were used to evaluate % uncertainty (Nakra and Choudhary, 1991).

$$U = \frac{\sqrt{\sigma_1^{\,2} + \sigma_2^{\,2} + \sigma_3^2 .... + \sigma_n^{\,2}}}{N}$$

Where σ is the standard deviation and is given as:

$$\sigma = \sqrt{\frac{\sum\left(X_i - \overline{X}_i\right)^2}{N_0}}$$

Where X_i is the moisture evaporated and $(X_i - \overline{X}_i)$ is the deviation of the observations from the mean. N and N_0 are the number of sets and number observations in each set, respectively.

The % uncertainty was determined using the following expression:

$$\%\text{ internal uncertainty} = \frac{U}{\text{Av. of total no. of observations}} \times 100$$

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