Experimental study on natural convection greenhouse drying of papad

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Abstract
In this paper, the convective heat transfer coefficients of papad for greenhouse drying under a natural convection mode are reported. Various experiments were conducted during the month of April 2010 at Guru Jambheshwar University of Science and Technology Hisar, India (29°5'5" N 75°45'55" E). Experimental data obtained for the natural convection greenhouse drying of papad was used to evaluate the constants in the Nusselt number expression by using simple linear regression analysis. These values of the constant were used further to determine the values of the convective heat transfer coefficient. The average value of a convective heat transfer coefficient was determined as 1.23 W/m² °C. The experimental error in terms of percent uncertainty was also evaluated.

Keywords: papad, papad drying, convective heat transfer coefficient, natural convection greenhouse

Nomenclature

A_t	Area of tray, m^2
C	Experimental constant
C_v	Specific heat of humid air, J/kg °C
g	Acceleration due to gravity, m/s^2
Gr	Grashof number = $\beta g X^3 \rho_v{}^2 \Delta T / \mu_v{}^2$
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}	Mass evaporated, kg
n	Experimental constant
N	Number of observations in each set
N_o	Number of sets
Nu	Nusselt number = h_c X/ K_v
Pr	Prandtl number = $m_v C_v / K_v$
$P(T)$	Partial vapour pressure at temperature T, N/m^2
$\dot{Q}_e$	Rate of heat utilized to evaporate moisture, J/m^2 s
T_p	Temperature of papad surface, °C
T_e	Temperature just above the papad surface, °C
T_g	Temperature inside the greenhouse, °C
t	Time, s
ΔT	Effective temperature difference, °C
X	Characteristic dimension, m

Greek symbols

β	Coefficient of volumetric expansion (K-1)
σ	Standard deviation
γ	Relative humidity (%)
λ	Latent heat of vaporization, J/kg
μ_v	Dynamic viscosity of humid air, Ns/m^2
ρv	Density of humid air, kg/m^3

1. Introduction

Papad is an important oriental snack food item particularly popular in South and South-East Asian countries. Its preparation involves gelatinization of the flour of different pulses with water contents generally varying from 27% to 30% per kg of papad weight. The kneaded dough is made into balls and then rolled with the help of a rolling pin into a circular thin disc of 130 mm to 210 mm diameter of thickness varying from 0.4 mm to 0.7 mm. It is dried by different means to a moisture level of 14% to 15% (Math *et al.,* 2004; Velu *et al.,* 2004; Kumar *et al.*, 2011; Parab *et al.,* 2012; Kamat and Yenagi, 2012; Teradal and Ravindra, 2013). Papad drying involves removal of moisture in order to preserve it. Though the preservation for enhanced life is the primary reason for drying, it also brings substantial reduction in weight and volume.

Papad drying is basically a heat and mass transfer process in which heat from the surrounding air and the sun transfers to the papad surface by different heat transfer modes. A part of this heat travels to the interior of papad and removes moisture from the interior to its surface by heat transfer taking the latent heat of vaporization. The remaining part of heat is utilized to increase the papad surface temperature which causes evaporation of the moisture to the surrounding air in the form of sensible heat.

Open sun drying is the most primitive (traditional) method of papad drying which is weather dependant and also prone to microbial and other contamination. In spite of many disadvantages, open sun drying is still practiced in places throughout the world. Although the hot air industrial driers are available to get the good quality of the product, they consume large amount of energy. The scarcity of fossil fuels, steep rise in the energy cost, and environmental pollution are the driving factors in the use of energy efficient and renewable drying processes. Solar energy is an important alternative source of energy and preferred to other energy sources because it is abundant, non-pollutant, and inexhaustible. Also, it is environmentally benign, cheap, and renewable which can be effectively used for drying purposes, if harvested properly. An advanced and alternative technique to the traditional method is greenhouse drying, in which the product is placed in trays and receives solar radiation through the plastic cover, while moisture is removed by natural convection or forced air flow. The uses of appropriate greenhouse dryers lead to reduction of drying time interval as well as improve the quality of the product in terms of texture, colour and taste. Furthermore, the contamination by insects, microorganisms, and bacteria can be prevented (Esper and Muhlbauer, 1998; Condori *et al.,* 2001; Tiwari, 2003; Kadam *et al*., 2011; Kumar, 2013).

The convective heat transfer coefficient is an important parameter in drying rate simulation, since the temperature difference between the air and the product varies with this coefficient (Anwar & Tiwari, 2001).The convective heat transfer coefficient depends on the physical properties of the humid air surrounding the papad and the temperature difference between the papad surface and the air. Papad research has been carried out by various workers relating to its diametrical expansion, water and oil absorption, chemical composition, texture, flavour, quality etc. (Bhattacharya & Narasimha, 1999; Math *et al*., 2004; Velu *et al.,* 2004; Nazni & Pradheepa, 2010; Parab *et al*., 2012; Veena *et al.,* 2012). Kumar *et al*., (2011) evaluated the convective heat transfer coefficients of papad drying under open sun and indoor forced convection conditions. The average values of convective heat transfer coefficients under open sun and forced convection drying modes were reported to be 3.54 W/m^2 °C and 1.56 W/m^2 °C respectively. Recently, Kumar (2013) evaluated the convective and evaporative heat transfer coefficients of papad under forced convection greenhouse mode. The average values of convective and evaporative heat transfer coefficients were determined as 0.759 W/m^2 °C and 23.48 W/m^2 °C respectively.

The usage of greenhouse for papad drying under natural convection mode is a new approach in papad preservation. The present study has been undertaken to evaluate the convective heat transfer coefficient of papad for greenhouse drying under natural convection. This research work would be helpful in designing a dryer for drying papad to its optimum storage moisture level of about 14% to 15%.

2. Materials and methods

2.1 Experimental set-up and instrumentation

A roof type even span greenhouse of 1.2×0.8 m^2 effective floor area was fabricated of PVC pipe and an ultraviolet film covering of thickness 200 microns. The central height and the walls were

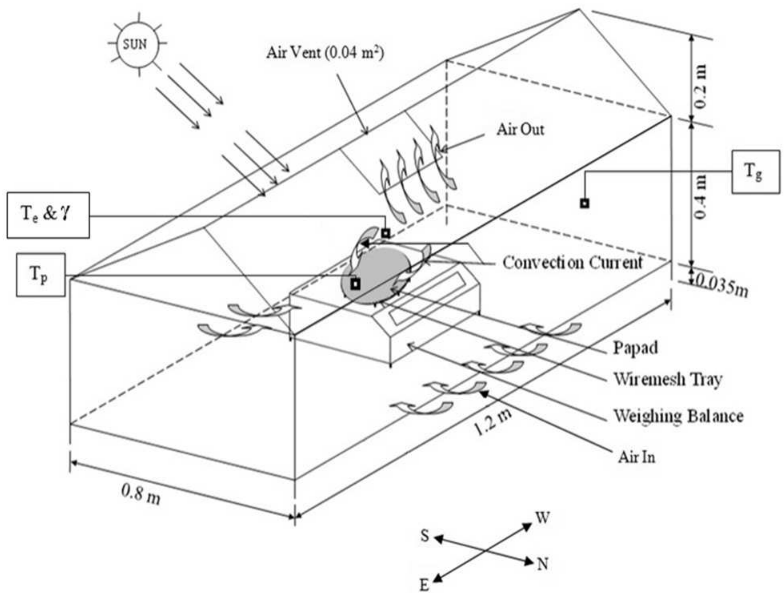

Figure 1: Schematic view of the experimental unit

maintained as 0.6 m and 0.4 m respectively. An air vent with an effective opening of 0.04 m^2 was provided at the roof for natural convection. The schematic view of the experimental unit for greenhouse drying in the natural convection mode is shown in Figure 1 and its photograph is shown in Figure 2.

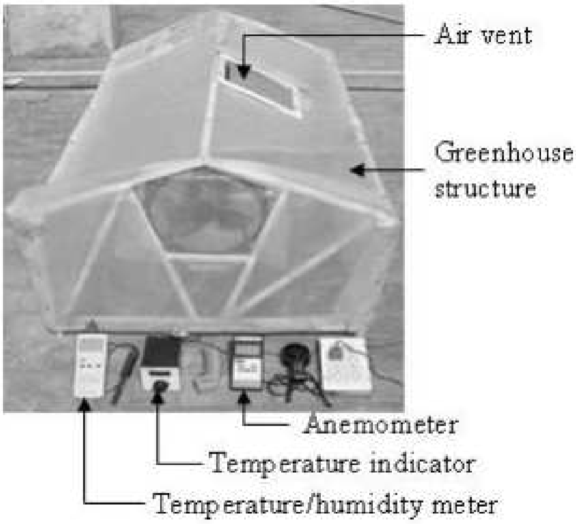

Figure 2: A photograph of an experimental unit for papad drying

A circular shaped wire mesh tray of diameter 0.180 m was used to accommodate the papad for single layer drying. It was kept directly over the digital weighing balance of 6 kg capacity (model TJ-6000, Scaletech, made in India) having a least count of 0.1 g. The papad surface temperature (T_p) and air temperature at different locations were measured by calibrated copper-constantan thermocouples connected to a ten channel digital temperature indicator with a least count of 0.1 °C (an accuracy of ±0.1%). The relative humidity () and the temperature just above the papad surface (T_e) was measured by a digital humidity/temperature meter (model Lutron-HT 3006, made in Taiwan). It had a least count of 0.1% relative humidity (an accuracy of ±3% on the full scale range of 10% to 95% of relative humidity) and 0.1 °C temperature (an accuracy of ± 0.8 °C on the full scale range of 50 °C).

2.2 Sample preparation and experimental observations

Papad was 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. The dough was kneaded and rolled in a circular shape of 0.7 mm thickness and 180 mm diameter with the help of pastry-board and pastry-roller. The freshly prepared papad of 23.5 g was used for each run of the greenhouse papad drying under natural convection.

Experiments were performed during the month of April 2010 at Guru Jambheshwar University of Science and Technology Hisar (29°5'5" N 75°45'55" E). The orientation of the greenhouse during the experimentation was kept east-west. Experimental setup was located on the open floor of a three-floor building to have a good exposure to the solar radiation. Each observation was taken for papad drying after half an hour time interval. The papad sample was kept in the wire mesh tray over the digital weighing balance. The moisture evaporated was calculated by taking the difference of mass of papad between two consecutive readings. The papad sample was dried till no variation in its mass was observed. In order to obtain accurate results, the experimentation procedure was repeated four times for each freshly prepared new papad sample of the same size (i.e., 180 mm diameter and 0.7 mm thickness) on consecutive days at the same timing. The initial mass of papad sample for each run of drying was kept constant (i.e., 23.5 g).

3. Theory

3.1 Thermal modelling

The convective heat transfer coefficient for evaporation under natural convection can be determined by using the following relations (Tiwari and Suneja, 1997; Kumar *et al.,* 2011):

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

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

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

On substituting h_c from Eq. (1), Eq. (2) becomes

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

The moisture evaporated is determined by dividing Eq. (3) by the latent heat of vaporization (λ) and multiplying the area of papad drying tray (*At*) and time interval (*t*).

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

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

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

Taking the logarithm of both sides of Eq. (5),

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

This is the form of a linear equation,

$$Y = mX_0 + C_0 \quad (7)$$

Where

$Y = \ln\left[\frac{m_{ev}}{Z}\right]$,

$m = n$,

$X_0 = \ln(Gr\,\mathrm{Pr})$, and

$C_0 = \ln C$

Thus, $C = e^{C_o}$

Values of m and C_0 in Eq. (7) are obtained by using the simple linear regression method by using the following formulae:

$$m = \frac{N\sum X_0 Y - \sum X_0 \sum Y}{N\sum X_0^{\,2} - \left(\sum X_0\right)^2} \quad (8)$$

and

$$C_0 = \frac{\sum X_0^{\,2}\sum Y - \sum X_0 \sum X_0 Y}{N\sum X_0^{\,2} - \left(\sum X_0\right)^2} \quad (9)$$

3.2 Experimental error

The experimental error was evaluated in terms of percent uncertainty (internal + external) for the moisture evaporated. The following two equations were used for internal uncertainty (Nakra and Choudhary, 1991):

$$U_I = \frac{\sqrt{\sigma_1^{\,2} + \sigma_2^{\,2} + \ldots \sigma_N^{\,2}}}{N_o} \quad (10)$$

and

$$\sigma = \sqrt{\frac{\sum\left(X - \bar{X}\right)^2}{N}} \quad (11)$$

Therefore, the percent internal uncertainty was determined using the following expression:

% internal uncertainty = (U_I/mean of the total observations) $\times 100$ (12)

For external uncertainty, the least counts of all the instruments used in measuring the observation data were considered.

3.3 Computation technique

The average of papad surface temperature (T_p) and temperature just above the papad surface (T_e) inside greenhouse were calculated at half an hour time intervals for corresponding moisture evaporated. The physical properties of humid air were evaluated for the mean temperature (T_i) of T_p and T_e by using the following equations (Kumar *et al.*, 2011):

$$C_v = 999.2 + 0.1434T_i + 1.101 \times 10^{-4}T_i^{\,2} - 6.7581 \times 10^{-8}T_i^{\,3} \quad (13)$$

$$K_v = 0.0244 + 0.7673 \times 10^{-4}T_i \quad (14)$$

$$\rho_v = \frac{353.44}{(T_i + 273.15)} \quad (15)$$

$$\mu_v = 1.718 \times 10^{-5} + 4.620 \times 10^{-8}T_i \quad (16)$$

$$P(T) = \exp\left[25.317 - \frac{5144}{(T_i + 273.15)}\right] \quad (17)$$

These physical properties of humid air were used for determining the values of the Grashof number (*Gr*) and Prandtl number (*Pr*). The values of constant *C* and exponent in the Nusselt number expression were determined by simple linear regression analysis and were used further to determine the values of convective heat transfer coefficient (h_c) from Equation (1) at the increment of every half an hour of observation.

4. Results and discussion

The experimental data obtained for papad drying under natural convection greenhouse mode are given in Tables 1–4.

Table 1: Observations for natural convection greenhouse drying of first papad sample (April 3, 2010)

Time	T_p (°C)	T_e (°C)	$m_{ev} \times 10^{-3}$ (kg)	γ (%)
9.30 am	36.6	42.4	3.1	35.6
10.00 am	40.0	45.0	2.6	38.2
10.30 am	41.4	45.2	1.8	36.0
11.00 am	44.4	46.8	1.3	35.3
11.30 am	50.2	51.5	1.1	36.4

Table 2: Observations for natural convection greenhouse drying of second papad sample (April 4, 2010)

Time	T_p (°C)	T_e (°C)	$m_{ev} \times 10^{-3}$ (kg)	γ (%)
9.30 am	37.8	42.8	2.8	36.8
10.00 am	41.2	43.8	2.5	39.4
10.30 am	42.6	44.0	2.0	37.2
11.00 am	45.6	45.6	1.5	36.5
11.30 am	51.4	50.3	1.0	37.6

Table 3: Observations for natural convection greenhouse drying of third papad sample (April 5, 2010)

Time	T_p (°C)	T_e (°C)	$m_{ev} \times 10^{-3}$ (kg)	γ (%)
9.30 am	38.0	42.0	2.9	37.0
10.00 am	41.4	44.0	2.6	39.6
10.30 am	42.6	44.2	2.2	37.4
11.00 am	45.8	45.8	1.2	37.5
11.30 am	51.8	50.2	1.0	37.8

Table 4: Observations for natural convection greenhouse drying of fourth papad sample (April 6, 2010)

Time	T_p (°C)	T_e (°C)	$m_{ev} \times 10^{-3}$ (kg)	γ (%)
9.30 am	37.2	42.6	3.0	36.2
10.00 am	40.6	44.4	2.7	38.8
10.30 am	42.0	44.6	1.9	36.6
11.00 am	45.0	46.2	1.4	35.9
11.30 am	50.8	50.9	1.1	35.1

The data given in Tables 1–4 were used to determine the values of constant and exponent *n* in the Nusselt number expression by simple linear regression analysis. Then the values of constant *C* and exponent *n* were considered further for determining the values of the convective heat transfer coefficient by Eq. (1). The values of constants (*C* & *n*) and the convective heat transfer coefficients for papad drying during natural convection greenhouse drying mode are presented in Table 5. The ranges of Grashof number were also given. The product of Grashof and Prandtl number indicates that the entire drying of papad for natural greenhouse mode falls within a laminar flow, because $Gr\ Pr \leq 10^7$ (Holman, 2004).

The values of constant and exponent were found to vary from 0.906 to 0.925 and 0.144 to 0.155 respectively. The convective heat transfer coefficients were observed to vary from 1.08 W/m² °C to 1.40 W/m² °C (Table 5). It was observed that different values of the convective heat transfer coefficient were obtained for similar papad sample dried on consecutive days. This variation could be due to change in operating conditions on each day.

It is observed from Tables 1–4 that the rate of moisture removal increases initially and then decreases for a given day. This can be explained in terms of the convective heat transfer coefficient. The variation of convective heat transfer coefficients with respect to drying time is illustrated in Figure 3. It can be seen from Figure 3 that the values of convective heat transfer coefficient decreases as the drying period progresses for the entire papad sample on each day. The average values of constants (&) and the convective heat transfer coefficient were also calculated which are presented in Table 6.

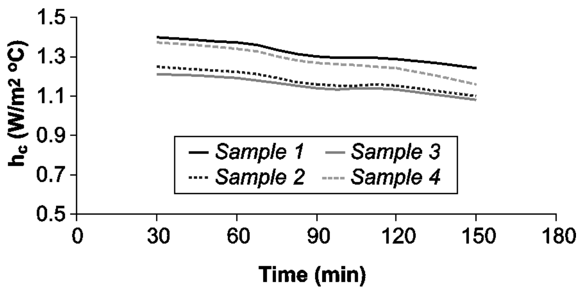

Figure 3: Variation of h_c versus drying time

Table 6: Average values of constants and the convective heat transfer coefficient

C	*n*	$h_{c,av}$ (W/m² °C)
0.920	0.149	1.23

Table 5: Values of experimentally evaluated parameters and the convective heat transfer coefficients

c	*n*	*Gr*	Pr	h_c (W/m² °C)
		First Papad Sample (April 3, 2010)		
0.924	0.154	$1.598 \times 10^6 - 4.403 \times 10^6$	0.695 – 0.696	1.24 – 1.40
		Second Papad Sample (April 4, 2010)		
0.925	0.146	$1.543 \times 10^6 - 4.288 \times 10^6$	0.695 – 0.696	1.10 – 1.24
		Third Papad Sample (April 5, 2010)		
0.925	0.144	$1.594 \times 10^6 - 4.242 \times 10^6$	0.695 – 0.696	1.08 – 1.21
		Fourth Papad Sample (April 6, 2010)		
0.906	0.155	$1.102 \times 10^6 - 3.862 \times 10^6$	0.695 – 0.696	1.16 – 1.37

The percent uncertainty (internal + external) was evaluated in the range of 33.71% to 38.92% for the natural convection greenhouse papad drying and the different values of the convective heat transfer coefficients were found to be within this range. The experimental percent uncertainties for papad drying under natural convection greenhouse mode are presented in Table 7. To show the variability of the convective heat transfer coefficients values from its true value (or error free value) SPSS software (Statistical Package for the Social Sciences, version 16.0) has been used which provided error bars with 95% confidence interval. The error bars for the convective heat transfer coefficients are illustrated in Figure 4.

Table 7: Experimental percent uncertainties

Sample number	*Internal uncertainty (%)*	*External uncertainty (%)*	*Total uncertainty (%)*
First	38.52	0.4	38.92
Second	33.31	0.4	33.71
Third	38.12	0.4	38.52
Fourth	36.16	0.4	36.56

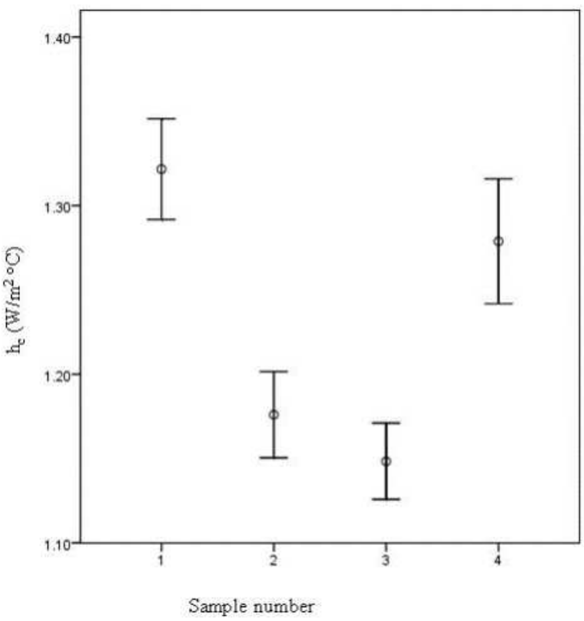

Figure 4: Error bars for the convective heat transfer coefficients

5. Conclusions

The research reported herein was set forth in order to evaluate the convective heat transfer coefficients for natural convection greenhouse drying of papad. The experimental data was analysed by using Nusselt number expression with the help of simple linear regression analysis. The average values of constant and exponent in the Nusselt number expression were found to be 0.920 and 0.149 respectively. The values of convective heat transfer coefficient were observed to vary from 1.08 W/m^2 °C to 1.40 W/m^2 °C. The average value of convective heat transfer coefficient for papad drying under natural convection greenhouse mode was found to be 1.23 W/m^2 °C. The experimental errors were evaluated within range of 33.71% to 38.94%. This research work would be helpful in designing a dryer for drying papad to optimum moisture level for retaining its quality during storage period.

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