Effect of mass on convective heat transfer coefficient during open sun drying of groundnut

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Abstract In this work, an attempt is made to study the effect of mass on convective heat transfer coefficient (CHTC) for open sun drying (OSD) of groundnut (*Arachis hypogaea* L.). Experiments were conducted during the month of May, 2016 in the climatic condition of Rohtak, India (28°54'0"N 76°34'0"E). Groundnut samples of 130 and 198 g were dried under OSD condition till almost no variation in its mass was recorded. Hourly data of the mass evaporated, groundnut temperature, relative humidity and ambient temperature were recorded. The experimental data obtained were used to determine the constants 'C' and 'n' in the Nusselt number expression using linear regression method. CHTC increased with the increase in mass of groundnuts. The experimental errors in terms of percent uncertainty were found to vary from 44.29 to 48.77%.

Keywords Groundnut/Peanut drying · Open sun drying · Convective heat transfer coefficient · Evaporative heat transfer coefficient

List of symbols

A_{tray} Wire mesh tray area (m^2)
 C Experimental constant

C_v Specific heat of the moist air ($J/kg\ ^\circ C$)
 g Acceleration due to gravity (m/s^2)
 Gr Grashof number = $gL^3\beta\rho^2\Delta T/\mu^2$
 h_c Convective heat transfer coefficient ($W/m^2\ ^\circ C$)
 $h_{c,avg}$ Average convective heat transfer coefficient ($W/m^2\ ^\circ C$)
 h_e Evaporative heat transfer coefficient ($W/m^2\ ^\circ C$)
 $h_{e,avg}$ Average evaporative heat transfer coefficient ($W/m^2\ ^\circ C$)
 K_v Thermal conductivity of the humid air ($W/m\ ^\circ C$)
 L Characteristics dimension = $[(l_{tray} + b_{tray})]/2$ (m)
 m_{ev} Moisture evaporated (kg)
 n Experimental constant
 Nu Nusselt number = $h_c L/K_v$
 Pr Prandtl number = $\mu_v C_v/K_v$
 $P(T)$ Partial vapour pressure at the temperature T, (N/m^2)
 Q_e Rate of heat utilized to evaporate moisture ($J/m^2\ s$)
 T_g Temperature of groundnut surface ($^\circ C$)
 T_e Temperature just above groundnut surface ($^\circ C$)
 t Time (s)
 ΔT Effective temperature difference ($^\circ C$)

Green symbols

β Coefficient of volumetric expansion ($1/K$)
 γ Relative humidity (%)
 μ_v Dynamic viscosity of the humid air ($N\ s/m^2$)
 ρ_v Density of the humid air (kg/m^3)
 σ Standard deviation
 λ Latent heat of vaporization (J/kg)

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Introduction

Groundnut/Peanut (*Arachis hypogaea* L.), king of oilseeds, belongs to bean family (Woodroof 1983). In developing countries, it is considered to be poor men's cashew nut. It is believed to be originated in South America (Zhao et al. 2012). India ranks second in groundnut production with an annual production of about 6 million metric tons (USDA 2015).

Groundnut is the chief oilseed crop in Southern Asia, especially in India (Dhamsaniya et al. 2012). It is extremely nutritious to health and rich source of edible oil (40–50%), protein (20–50%), minerals and vitamins (Sahdev et al. 2015; Arya et al. 2016). Indian groundnuts are very popular because of its flavour, taste and crunchiness. Export of groundnuts have reached more than 7 Lac tons during 2014–2015 (APEDA 2016).

Groundnuts need to be dried to the safe moisture content (8–10%) for longer shelf life. Otherwise fungus may occur and spoil the groundnuts. In developing countries, farmers dry groundnuts by exposing under open sun. Open sun drying (OSD) is undoubtedly the simplest and cheapest method of groundnut drying (Purkayastha et al. 2013). Drying of any product is essentially the phenomenon of heat and mass transfer (Jayashree et al. 2014). A portion of the sun radiation incident on the uneven surface of the groundnut reflects back into the environment. The remaining part of the sun energy is absorbed by the product surface and hence increases the product surface temperature. Heat absorbed by the product results in various losses, such as mass transfer, convection losses and so on, to the atmospheric air through the moist air. The product gets dried due to water evaporation in the form of evaporative losses. Some portion of the absorbed energy (thermal) gets penetrated into the product interior and thus inside temperature of the product is increased which propagates the water vapour formation inside the product. Then the diffusion of water vapour gets started and the mass of the product decreases (in the form of moisture evaporation) from the surface of the product (Tiware et al. 2016a, b). Groundnut drying is essentially the phenomenon of heat and mass transfer.

The convective heat transfer coefficient (CHTC) which is an important parameter in drying rate simulation as the temperature difference varies with this coefficient. Anwar and Tiwari (2001) studied the drying of six crops under OSD mode and evaluated the CHTC whose values were found to lie in the range of 3.71–25.98 W/m² °C. Togrul (2003, 2005) investigated the drying of nine crops and apricots under OSD mode and determined the CHTC. The values of CHTC were reported to lie within the range of 0.0374–3.3 W/m² °C. Prasad and Vijay (2005) carried out the studies for the drying of *Tinospora cordifolia*, *Curcuma longa* and *Zingiber officinale* under OSD condition and

calculated the value of CHTC. The value of CHTC was observed to vary from 1.57 to 3.85 W/m² °C. Jain (2006) presented the drying of fish under OSD mode and the value of CHTC was reported to lie between 0.320–8.958 W/m² °C. Kumar and Tiwari (2007) studied the effect of mass for the drying of onion under OSD and greenhouse drying (GHD) modes. The values of CHTC were observed to lie in the range of 1.09–2.75 and 1.10–3.08 W/m² °C under OSD and GHD modes respectively. Prasad (2009) also studied the drying of spices and herbs under OSD mode and determined the CHTC whose value was reported to vary from 1.527 to 3.88 W/m² °C. Kumar et al. (2011) carried out the study of papad (food product) under OSD and indoor forced convection drying (IFCD) modes. The computed value of CHTC was reported to be 3.54 and 1.56 W/m² °C under OSD and IFCD conditions respectively.

Some authors have also attempted to dry groundnuts by various means which are discussed here. Ahmed et al. (1967) carried out the comparative studies under open sun and accelerated drying of groundnuts. Nawungkalatusart and Tamtawatchai (1989) investigated the continuous drying of groundnuts at different temperatures. Drying at 55 °C was observed to be suitable for germination of groundnut seeds. Gowda et al. (1991) presented the drying of groundnut seeds of different moisture contents (35, 43 and 67% db) at different air temperatures. Noomhorm et al. (1994) presented the drying of groundnuts under sun and rotary type conduction dryer. Conduction dryer was reported to be better than the former. Syarif et al. (1996) studied the peanut seed drying in a free convection dryer which used coconut stone as fuel. Tarigan and Tekasakul (2005) presented the peanut drying inside indirect solar dryer. The system efficiency was reported to be 23%. Ahmed and Mirani (2012) presented low cost mobile flat-bed dryer for drying groundnuts in which the moisture content was maintained up to 14%. Mennouche et al. (2014, 2015) proposed the solar indirect and direct dryers for the drying of peanuts. The yield was observed to be increased up to 42.87%.

It is observed from the literature that various commodities have been dried under OSD mode and the values of CHTC for drying these commodities lie in the range of 0.0374–25.98 W/m² °C. Groundnut has also been dried by different means such as mechanical dryers, forced dryers, conduction, direct and indirect solar dryers etc. But work on groundnuts under open sun conditions have not been found in the open literature. Determination of convective heat transfer coefficient is helpful in the design of a dryer. Thus the previous work has prompted us to study the effect of mass on CHTC for drying of groundnuts under OSD mode, which will be supportive in future design of a better dryer for drying the groundnuts to its optimal storage moisture content of 8–10%.

Materials and methods

Experimental setup and instrumentation

The photograph and schematic view of the experimental setup under OSD mode is shown in Fig. 1. A rectangular wire mesh tray of $25 \times 15 \text{ cm}^2$ was used to accommodate the groundnuts in a single thin layer. An electronic digital weighing balance (capacity: 6 kg, least count = 0.1 g) was used to measure the mass of moisture evaporated. A non-contact infrared thermometer (model: Raytek-MT4, least count = 0.2°C , accuracy = $\pm 2\%$ on a full scale range of -1 to 400°C) was used to measure the groundnut surface temperature. A ten channel digital temperature indicator (range of 0 – 200°C , least count = 0.1°C) with calibrated thermocouples was used to measure the atmosphere (ambient) temperature. The thermocouples were calibrated by a ZEAL standard thermometer. A digital hygrometer (Model: Lutron, Taiwan, HT-315) was used to measure the temperature and relative humidity (RH) just above the groundnut surface. A solar power meter (Model MECO-936, India, least count = 1 W/m^2 having an accuracy of $\pm 10 \text{ W/m}^2$) was used to measure solar intensity. An anemometer (Model: Lutron AM-4201, Taiwan, least count = 0.1 m/s) was used to measure the wind velocity at groundnut surface.

Sample preparation

Fresh groundnuts were purchased directly from the farmer and cleaned to remove broken and immature pods. Groundnuts were remoistened by soaking in water for 12 h.

After 12 h samples were conditioned in shed for 1 h so that the extra water gets removed. Then the samples were used for experimentation.

Experimental procedure

Experiments were performed in the May month of 2016 for OSD condition in the climatic conditions of Rohtak ($28^\circ 54' \text{N}$ $76^\circ 34' \text{E}$), India. Groundnuts of 130 g (Sample 1) and 198 g (Sample 2) were spread in thin layer on wire mesh tray of size $25 \times 15 \text{ cm}^2$ and then the tray was kept on the weighing balance. A hygrometer (digital) was kept just above the groundnut surface with its probe facing downwards towards the surface of the groundnut to measure the RH and temperature of the humid air. The hygrometer was kept on 2 min before recording the observation. The thermocouples connected with digital temperature indicator were placed at various places to measure the temperature of groundnut surface. All the observations were recorded hourly. The whole experimental set up was kept in open sun at a place without disturbance of wind. The difference of two successive readings of the weighing balance gave the water evaporated during that time interval. The average values of groundnut surface ($T_{g, avg}$) and exit air ($T_{e, avg}$) temperatures and RH (γ_{avg}) were determined from two successive values for that time interval and were used in the calculations.

Thermal modelling

CHTC can be determined by Eq. (1) of the Nusselt number expression (Kumar et al. 2011; Tiwari 2014).

Fig. 1 Photograph (a) and schematic view (b) of the experimental setup under OSD mode

$$Nu = \frac{h_c L}{K_v} = C \times (Gr Pr)^n \quad (1)$$

or

$$h_c = \frac{K_v}{L} C (Gr Pr)^n \quad (2)$$

The rate of heat utilized to evaporate the moisture is determined by using Eq. (3) (Kumar et al. 2012a; Kumar 2013; Tiwari et al. 2016a).

$$Q_e = 0.016 h_c [P(T_g) - \gamma P(T_e)] \quad (3)$$

Substituting the value of h_c (CHTC) from Eqs. (2), (3) becomes

$$Q_e = 0.016 \times \frac{K_v}{L} C \times (Gr Pr)^n \times [P(T_g) - \gamma P(T_e)] \quad (4)$$

The evaporation of moisture is determined by dividing Eq. (4) by the latent heat of vaporization (λ) and multiplying by the area of tray (A_{tray}) and time interval (t).

$$\begin{aligned} m_{ev} &= \frac{Q_e}{\lambda} t A_{tray} \\ &= 0.016 \times \frac{K_v}{L \lambda} C \times (Gr Pr)^n \times [P(T_g) - \gamma P(T_e)] t A_{tray} \end{aligned} \quad (5)$$

$$\text{Let } 0.016 \frac{K_v}{L \lambda} [P(T_g) - \gamma P(T_e)] t A_{tray} = Z$$

$$\therefore \frac{m_{ev}}{Z} = C \times (Gr Pr)^n \quad (6)$$

Taking the logarithm on both sides of Eq. (6), we get

$$\ln \left[\frac{m_{ev}}{Z} \right] = \ln C + n \times \ln(Gr Pr) \quad (7)$$

Here, Eq. (7) is the arrangement of a linear equation

$$y = m \times x + c \quad (8)$$

where $y = \ln \left[\frac{m_{ev}}{Z} \right]$, $m = n$, $x = \ln(Gr Pr)$, $c = \ln C$. Therefore, $C = e^c$. The values of the experimental constants m

and c in Eq. (8) are evaluated by using simple linear regression formulae. The evaporative heat transfer coefficients (EHTC) are evaluated by using the Eq. (9) (Kumar et al. 2012b; Sahdev et al. 2016).

$$h_e = 0.016 h_c \left[\frac{P(T_g) - \gamma P(T_e)}{T_g - T_e} \right] \quad (9)$$

The properties (thermo-physical) of the moist air were calculated for the mean temperature $T_i = \left[\frac{(T_g + T_e)}{2} \right]$ by using the equations from (10) to (14) (Anwar and Tiwari 2001; Kumar 2016).

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

$$\mu_v = 1.718 \times 10^{-5} + 4.620 \times 10^{-8} T_i \quad (11)$$

$$C_v = 999.2 + 0.1434 T_i + 1.101 \times 10^{-4} T_i^2 - 6.7581 \times 10^{-8} T_i^3 \quad (12)$$

$$\rho_v = \frac{353.44}{T_i + 273.15} \quad (13)$$

$$P(T) = \exp \left[25.317 - \frac{5144}{T + 273.15} \right] \quad (14)$$

Results and discussion

The data collected from drying of groundnut samples 1 and 2 under OSD mode are shown in Table 1. These data were used to evaluate the values of the experimental constant C and exponent n in Eq. (1) for Nusselt number expression (Nu) by using the simple regression method. The values of these constants were used in Eq. (2) for determining the values of CHTC. The values of CHTC (h_c) were used in Eq. (9) to calculate the values of EHTC (h_e). The computed values of h_c, h_e , constants C and n and experimental error in terms of percent uncertainties (internal and external) are tabulated in Table 2.

Table 1 Experimental data for samples 1 and 2

Time	T_g (°C)	T_e (°C)	$m_{ev} \times 10^{-3}$ (kg)	γ (%)	$Gr \times 10^5$	Pr	T_g (°C)	T_e (°C)	$m_{ev} \times 10^{-3}$ (kg)	γ (%)	$Gr \times 10^5$	Pr
Data for sample 1							Data for sample 2					
7–8 am	28.3	31.89	10.0	46.07	50.5	0.698	27.9	32.26	15.7	46.45	55.1	0.698
8–9 am	33.4	35.63	12.0	34.74	24.8	0.697	33.6	36.25	18.3	34.75	23.3	0.697
9–10 am	38.7	38.92	5.0	29.24	5.98	0.696	39.0	39.38	7.0	28.92	8.63	0.696
10–11 am	41.1	41.32	6.0	26.90	13.6	0.696	42.0	41.03	9.0	27.75	21.6	0.696
11–12	43.5	43.01	2.6	24.25	16.8	0.696	44.7	42.22	4.0	26.19	26.6	0.696
12–1 pm	46.8	45.08	2.2	21.88	26.5	0.695	47.8	43.51	2.7	24.33	34.7	0.695
1–2 pm	49.6	47.18	2.2	19.67	36.2	0.695	49.4	45.05	2.3	22.48	34.7	0.695
2–3 pm	51.1	48.17	2.0	17.25	39.2	0.695	49.5	46.69	2.0	19.45	27.8	0.695
3–4 pm	49.5	48.92	1.0	15.58	28.8	0.695	48.5	47.10	2.0	17.80	21.7	0.695

Table 2 Values of C , n , h_c , h_e and experimental percent uncertainties for groundnut drying

Sample no.	C	n	h_c (W/m ² °C)	$h_{c, avg}$ (W/m ² °C)	h_e (W/m ² °C)	$h_{e, avg}$ (W/m ² °C)	Internal uncertainty (%)	External uncertainty (%)	Total uncertainty (%)
1	1.07	0.11	0.61–0.77	0.71	5.61–236.28	106.24	44.29	0.6	44.89
2	0.99	0.14	0.87–1.10	1.03	6.08–163.89	63.82	48.17	0.6	48.77

Fig. 2 Variation in h_c and h_e with time

It can be seen from Table 1 that the moisture evaporation occurs faster during initial hours and then decreases as the day progresses. The values of the experimental constants C and n for drying of groundnut samples 1 and 2 were observed to be 1.07 and 0.11 and 0.99 and 0.14 respectively. The values of CHTC for groundnut samples 1 and 2 were found to vary from 0.61–0.77 and 0.87–1.10 W/m² °C respectively. The average values of CHTC for the groundnut samples 1 and 2 were found to be 0.71 and 1.03 W/m² °C respectively. Thus it can be concluded that the value of CHTC increases with the increase in groundnut mass which is in accordance with those reported in literature (Kumar and Tiwari 2007). The values of EHTC for the groundnut samples 1 and 2 were observed to vary from 5.61–236.28 to 6.08–163.89 W/m² °C respectively. The variations in convective (h_c) and evaporative (h_e) heat transfer coefficients with respect to time for both samples are shown in Fig. 2. The range of Grashof numbers is also evaluated which is specified in Table 1. The product of Gr and Pr indicates that the whole drying for both the samples falls within the laminar region, since $Gr Pr \leq 10^7$ (Kumar 2013).

The CHTC for nine crops (Pear, green pepper, marrow, potato, carrot, Albanian pepper, aubergine, onion and green bean) were reported to vary from one crop to another crop with a range of 0.25–3.29 W/m² °C (Togrul 2003). The calculated values of CHTC for the groundnut drying in the present research work are observed to lie in the given

range. The photographic views of the groundnut samples 1 and 2 before and after drying are presented in Fig. 3.

The error bars (the graphical representation of the variability of the data) are used to show the error in the measurements of the CHTC and EHTC. The variability in the CHTC and EHTC from its true value is shown by error bars (95% confidence interval) in Fig. 4. The error bars are drawn with the help of SPSS software (version 24).

Conclusion

In the present work, the values of CHTC and EHTC for different masses of groundnut drying under OSD mode were evaluated. The experimental data were analyzed by using the expression of Nusselt number by using simple linear regression method. The following conclusions were made from this work.

1. The value of CHTC varied from 0.61–0.77 to 0.87–1.10 W/m² °C for the drying of sample 1 and sample 2 respectively.
2. The average values of CHTC for sample 1 and sample 2 were 0.71 and 1.03 W/m² °C respectively.
3. It was concluded that the value of CHTC increased with increase in groundnut mass.
4. The average values of EHTC for sample 1 and 2 were observed to be 106.24 and 63.82 W/m² °C respectively.

Fig. 3 Groundnut samples 1 and 2 before and after drying

Fig. 4 Error bars for the convective and evaporative heat transfer coefficients

- The experimental errors in terms of percent uncertainty (sum of internal and external) for samples 1 and 2 were calculated to be 44.89 and 48.77% respectively.
- Determination of convective heat transfer coefficient is required for the proper design of a dryer. Thus the present research work may be useful in future designing a better groundnut dryer to retain its quality during storage period.

where X_i = moisture evaporated, and $(X_i - \bar{X}_i)$ = deviation of the observations from the mean value. N = number of sets, and N_o = number of observations in each set.

The percent uncertainty was evaluated as

$$\% \text{ internal uncertainty} = \frac{U^*}{\text{Average of total number of observations}} \times 100 \quad (17)$$

Appendix

The errors (experimental) were determined in terms of internal and external percent uncertainties for the mass evaporated. The Eqs. (15)–(17) were used to calculate internal uncertainty (Tiwari 2014).

$$U^* = \frac{\sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \dots + \sigma_n^2}}{N} \quad (15)$$

where σ is the standard deviation and is given as

$$\sigma = \sqrt{\frac{\sum (X_i - \bar{X}_i)^2}{N_o}} \quad (16)$$

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