Experimental free convection thin layer groundnut greenhouse drying

Mahesh Kumar[1], Ravinder Kumar Sahdev[2*], Sumit Tiwari[3], Hitesh Panchal[4], Himanshu Manchanda[1]

(1. *Department of Mechanical Engineering, Guru Jambheshwar University of Sciences & Technology, Hisar, India, 125001*;
2. *Department of Mechanical Engineering, University Institute of Engineering & Technology, Maharshi Dayanand University, Rohtak, Haryana, India, 124001*;
3. *Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi, Delhi – 110016*;
4. *Department of Mechanical Engineering, Government Engineering College, Patan, Gujarat, India, 384002*)

Abstract: The groundnuts were dried inside an even span roof type free convection greenhouse dryer with a useful floor area of 1.2×0.8 m^2 in the environmental conditions of Rohtak, India (28°54′-N 76°34′E). Wire mesh sieves of sizes 0.15×0.25 m^2, 0.25×0.4 m^2, and 0.35×0.6 m^2 were used to accommodate thin layer samples of groundnuts. The groundnuts were dried till the optimum safe moisture storage level (8%-10%) was attained. Based on experimental (hourly) observations the values of constants (C and n) in the equation of Nusselt number were evaluated. The values of convective and evaporative heat transfer coefficients were calculated which were observed to decrease with the increase in the sieve size. The overall average greenhouse thermal, energy, and exergy efficiencies were evaluated as 8.83%, 22.67%, and 2.75% respectively. The overall average experimental error in terms of % uncertainty for groundnuts drying was evaluated as 37.94%.

Keywords: groundnut/peanut, greenhouse drying, convective heat transfer coefficient, evaporative heat transfer coefficient, free convection

Citation: Kumar, M. R. K. Sahdev, S. Tiwari, H. Panchal, and H. Manchanda. 2019. Experimental free convection thin layer groundnut greenhouse drying. Agricultural Engineering International: CIGR Journal, 21(3): 203–211.

1 Introduction

The groundnut (*Arachis hypogaea* L.), important oilseed crop belongs to Fabaceae family and originated in South America. It is the great source of nutrition. It is also known as ‘King of Oilseeds’ and is considered to be poor man’s cashew nut (Sahdev et al., 2015, Sahdev et al., 2017a). It is grown on about 24 million hectares worldwide with total production of 42.24 million metric tons (USDA, 2017). India is the second most groundnut producing (6.64 million-metric tons) country in the world (USDA, 2017). It is an important food and rich source of protein (20%-50%) and oil (40%-50%) (Sahdev et al., 2017b). Export of Indian groundnuts have reached about 7.26 Lac tons during 2016-17 (APEDA, 2017).

If groundnuts are not dried to its safe moisture level of 8%-10% (w.b.), fungus may deteriorate the seed quality for further consumption. Developing countries do not have good drying and storage facilities. Groundnuts are spread on ground exposing directly to sun radiations for about 2-5 days to dry to their safe moisture level. Open sun drying (OSD), traditional method of food preservation technique, is certainly the cheapest method of drying because it does not require any extra source of energy. But quality of the products dried in OSD degrades and does not meet the international standards due to limitations such as discolouring of the product due to ultraviolet rays, insect infestation and microorganisms. About 30%-40% of agricultural products are estimated to be spoiled during postharvest processes (Sahdev et al., 2019). The postharvest losses of groundnuts in Asia are

Received date: 2018-07-16 **Accepted date:** 2018-10-31
*** Corresponding author: Ravinder Kumar Sahdev,** Assistant Professor, Department of Mechanical Engineering, University Institute if Engineering & Technology, Maharshi Dayanand University, Rohtak, 124001, Haryana, India. Email: ravindersahdev1972@gmail.com, Telephone No; +919466547373, Fax No: 01262-274640.

about 10%-25% of its production (Ranga Rao et al., 2010). Therefore, greenhouse drying (GHD), an advanced and alternative method can be used to overcome the limitations of OSD. In GHD, crop receives the solar radiations through the UV stabilized plastic sheet and water vapour (moisture) is removed by free or forced air flow (Tiwari et al., 2016). The proper use of GHD retains the product quality as well as shortens the drying time (Condori et al., 2001).

The convective heat transfer coefficient (h_c) is the most important factor in drying rate simulation, as the temperature difference between the air and the groundnut varies with this coefficient. Farhat et al. (2004) proposed pepper drying in polyethylene greenhouse under free convection mode. Jain and Tiwari (2004) presented cabbage and peas drying under OSD, free, and forced modes of GHD. The value of h_c was found to lie between 2 to 17 W m^{-2} ^{o}C^{-1}, and 2 to 25 W m^{-2} ^{o}C^{-1} under GHD and OSD modes respectively. Koyuncu (2006) carried out the comparative analysis of pepper drying under OSD and natural convection greenhouse drying (NCGHD) modes in which NCGHD mode was reported to be 2 to 5 times more efficient than OSD condition. Kumar and Tiwari (2007) studied the onion drying under OSD, and GHD conditions. The values of h_c were reported to vary from 1.09 to 3.08 W m^{-2} ^{o}C^{-1}, and 1.19 to 2.75 W m^{-2} ^{o}C^{-1} under GHD, and OSD modes respectively. Ayyappan and Mayilswamy (2010) presented the copra drying in a natural convection solar tunnel dryer whose efficiency was observed to be 20%. Ayyappan et al. (2015) investigated the drying of copra under free convection greenhouse drying using different sensible heat storage materials (i.e., rock-bed, sand, and concrete). Among these, rock-bed (with 11.65% efficiency) was reported to be best.

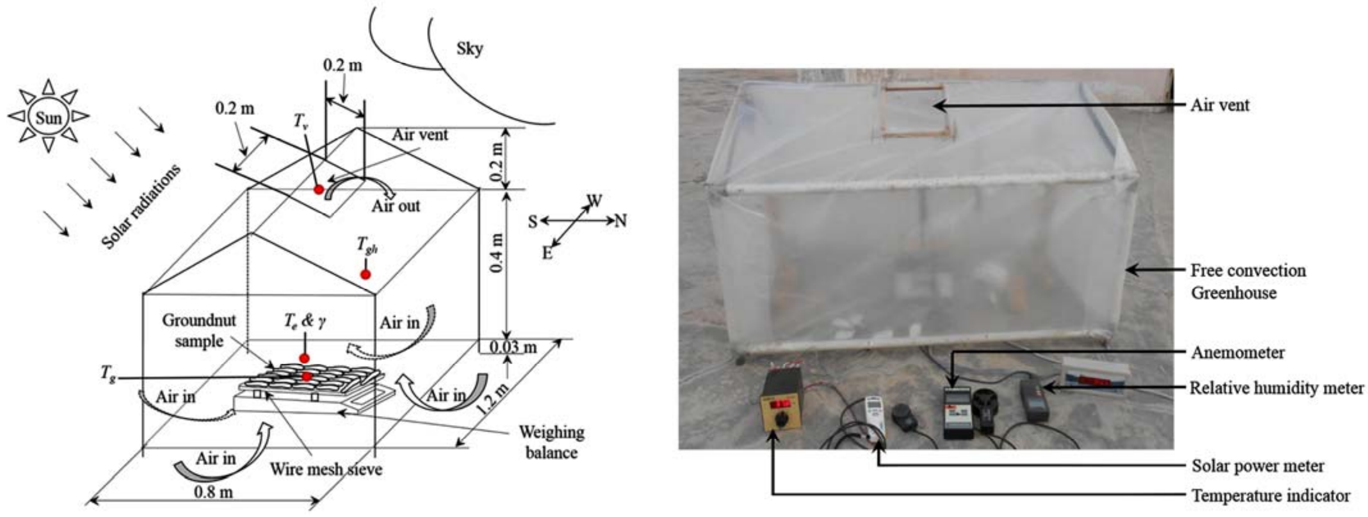
Many authors have also studied the drying of groundnut by different means such as double trailer drying (Blankenship and Chew, 1979), microwave vacuum drying (Delwiche et al., 1986), continuous drying at various temperatures (Nawungkalatusart and Tamtawatchai, 1989), rotary dryer (Noomhorm et al., 1994), natural convection dryer using coconut stones as fuel (Syarief et al., 1996), rack type dryer (Tumbel et al., 1997), semi-trailer dryer (Ertas et al., 1999), batch type dryer (Palacios et al., 2004), indirect solar dryer (Tarigan and Tekasakul, 2005), modified solar grain dryer (Ezekoye and Enebe, 2006), mobile flat-bed dryer (Ahmed and Mirani, 2012), and direct, and indirect natural solar dryers (Mennouche et al., 2014; Mennouche et al., 2015). Sahdev et al. (2017b) investigated the effect of mass on h_c for open sun drying of groundnuts kept in a wire mesh tray of size 25×15 cm^2. The value of h_c was found to vary from 0.61 to 1.10 W m^{-2} ^{o}C^{-1}. The value of h_c was found to increase with increase in mass of groundnut. Sahdev et al. (2017c) determined h_c and evaporative heat transfer coefficient (h_e) of groundnut drying under indoor forced convection drying (IFCD) mode whose values were found to vary from 2.45 to 2.49 W m^{-2} ^{o}C^{-1} and 28.08 to 38.73 W m^{-2} ^{o}C^{-1} respectively. Recently, Sahdev et al. (2018) investigated the groundnut drying under FCGHD mode, for which values of h_c and h_e were reported to lie in the range of 0.41 to 1.85 W m^{-2} ^{o}C^{-1} and 4.07 to 489.62 W m^{-2} ^{o}C^{-1} respectively. The value of h_c was found to decrease with the increase in wire mesh size. The average values of greenhouse thermal efficiency, energy efficiency, and exergy efficiency were found to vary from 7.49% to 11.90% and 54.4% to 77.92%, and 0.95% to 2.57% respectively.

It is seen from the literature review that number of crops have been dried under free convection GHD mode. Groundnuts have also been dried by artificial and mechanical methods which require extra source of energy and thus making it costly. To the best of author's knowledge no study is available in the literature on the thin layer (single layer) groundnut drying under free convection GHD mode. In the current study, effect of wire mesh sieve sizes on h_c and h_e during free convection GHD of groundnuts have been determined. The thermal performance of free convection greenhouse dryer for groundnut drying has also been determined. Present study would be supportive in the designing of an efficient dryer for drying groundnuts to their safe storage moisture content.

2 Materials and methods

2.1 Experimental setup and instrumentation

An even span roof type greenhouse structure (1.2 m× 0.8 m useful floor area) was covered with 0.2 mm thick ultraviolet treated sheet. It's central height was kept at 0.6 m and wall height was kept as 0.4 m. An air vent of 0.2 m×0.2 m was provided at the roof for free convection and a clearance of 3 cm was provided at the bottom of the greenhouse dryer for fresh air circulation. The schematic view and photograph of the experimental set up are shown in Figure 1(a) and 1(b) respectively. It was located on the roof of the two floor building to get the maximum exposure to the solar radiations. The greenhouse was kept in east-west position for optimum utilization of solar radiations. The experiments were carried out with three wire mesh sieve of sizes 0.15×0.25 m^2, 0.25×0.4 m^2, and 0.35×0.6 m^2 which accommodated the single layer (thin layer) of groundnuts. Groundnuts samples in single layer were kept in a wire mesh sieve directly over the digital weighing balance (Smart, India; range: 0-6 kg, and least count: 0.1 g). The groundnut temperature (T_g) and greenhouse room temperature (T_{gh}) at various places were measured by calibrated thermocouples (Copper constantan, range: –50°C to 200°C, and least count: 0.1°C) which were connected to a twelve channels digital temperature indicator (Creative, India, Range: 0°C-300°C, least count: 0.1°C). The thermocouples were calibrated with respect to a ZEAL thermometer which gives precise readings. The temperature just above the groundnut surface (T_e) and the relative humidity (γ) were measured by a digital hygrometer (Lutron – 315, Taiwan, range: 0°C-100°C, 0%-100% γ, and least count: 0.1°C, 0.1% γ). The intensity of solar radiation was measured using a solar power meter (model MECO – 936, India, range: 0-2000 W m^{-2}, and least count: 1 W m^{-2}). The wind velocity was measured with an anemometer (model Lutron, AM – 4201, Taiwan, range of 0-30 m s^{-1}, and least count of 0.1 m s^{-1}).



(a) (b)

Figure 1 Schematic view and photograph of free convection greenhouse dryer

2.2 Sample preparation and experimental procedure

Fresh groundnuts were procured and cleaned to remove immature pods and foreign materials. The groundnut samples for experimentation were remoistened by soaking in water for about eight hours and then were kept in shed for one hour to remove the extra moisture.

Experiments were performed during April 2016 in the environmental conditions of Rohtak, India (28°54′N 76°34′E). Groundnut samples in single layer (thin layer) were kept in wire mesh sieve of sizes 0.15×0.25 m^2 (Sample 1), 0.25×0.4 m^2 (Sample 2), and 0.35×0.6 m^2 (Sample 3) over the weighing balance (digital). The water vapour evaporated (m_{ev}) during the observed time interval was determined by taking the difference of groundnut mass between two successive hourly readings. The data (hourly) for m_{ev}, T_g, γ, T_e, T_{gh}, vent temperature (T_v) and ambient temperature (T_{amb}) were recorded. The groundnut samples were dried to its optimum safe moisture level.

2.3 Thermal modeling

The convective heat transfer coefficient (h_c) for the groundnut drying inside free convection GHD is evaluated using Equation (1) given by Kumar et al. (2011):

$$Nu=h_cX_d/K_v=C(Gr\,\mathrm{Pr})^n \tag{1}$$

$$h_c=(K_v/X_d)\times C(Gr\,\mathrm{Pr})^n \tag{2}$$

The rate of heat utilized to evaporate water vapour present in the drying product (Q_e) is given as (Kumar, 2013):

$$Q_e=0.016\times h_c\times[P(T_g)-\gamma P(T_e)] \tag{3}$$

Substituting the value of h_c from Equation (2), Equation (3) becomes

$$Q_e=0.016\times(K_v/X_d)\times C\times(Gr\,\mathrm{Pr})^n[P(T_g)-\gamma P(T_e)] \tag{4}$$

The water vapour evaporated (m_{ev}) is evaluated by dividing the Equation 4 by the latent heat of vaporization (λ) and multiplying by the area of the sieve (A_t) and time interval (t).

$$m_{ev}=(Q_e/\lambda)\times tA_t=0.016\times K_v/(X_d\times\lambda)\times C\times(Gr\,\mathrm{Pr})^n$$
$$[P(T_g)-\gamma P(T_e)]tA_t \tag{5}$$

$$\therefore\quad m_{ev}/Z=C\times(Gr\,\mathrm{Pr})^n \tag{6}$$

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

$$\ln[m_{ev}/Z]=\ln C+n\ln(Gr\,\mathrm{Pr}) \tag{7}$$

Equation (7) is the formation of a linear equation

$$y=mx+c \tag{8}$$

where, $y=\ln[m_{ev}/Z]$, $m=n$, $x=\ln(Gr\,\mathrm{Pr})$, and $c=\ln C$, Thus, $C=e^c$.

The values of constants (m and c) in Equation 8 are achieved by using simple linear regression formula. The evaporative heat transfer coefficient was evaluated (Kumar et al., 2012) as,

$$h_e=0.016\times h_c\times\{[P(T_g)-\gamma P(T_e)/(T_g-T_e)] \tag{9}$$

2.4 Thermal efficiency, energy efficiency, and exergy efficiency of greenhouse dryer

Thermal efficiency of greenhouse dryer is defined as the ratio of energy which is used to evaporate the water vapour from the groundnut to the energy delivered to the greenhouse through the solar radiations and is evaluated as (Sahdev et al., 2016):

$$\eta_{th}=(m_{ev}\times\lambda)/[\sum(I_i\times A_i)\times t] \tag{10}$$

The energy input to the greenhouse can be expressed by Equation (11) (Tiwari and Tiwari, 2017):

$$En_{i/p}=\sum(I_iA_i)\times\alpha_g\tau+\sum(I_iA_o)\times\alpha_{gnd}\tau \tag{11}$$

Energy output is given as (Sahdev et al., 2016):

$$En_{o/p}=0.33\times N_{ap}V_{gh}(T_{gh}-T_{amb})+m_{ev}\lambda \tag{12}$$

Energy efficiency is determined by Equation (13)

$$\eta_{En}=(En_{o/p}/En_{i/p})\times 100 \tag{13}$$

Exergy can be expressed as the maximum amount of useful work which can be obtained from a greenhouse (Tiwari and Tiwari, 2017). The exergy input is given by Equation (14) (Sahdev et al., 2018) as,

$$Ex_{in}=(\sum I_iA_i)\times[1-(4/3)\times(T_{amb}/T_{sun})+(1/3)\times(T_{amb}/T_{sun})] \tag{14}$$

Exergy output is given by Equation (15) (Sahdev et al., 2018a) as,

$$Ex_{o/p}=M_{ao}C_a\times\{(T_v-T_{amb})-(T_{amb}+273.15)\times$$
$$\ln[(T_v+273.15)/(T_{amb}+273.15)]\} \tag{15}$$

Exergy efficiency is given by Equation (16) as,

$$\eta_{Ex}=(Ex_{o/p}/Ex_{i/p})\times 100 \tag{16}$$

2.5 Computation technique

The mean of T_g and T_e were determined hourly for corresponding value of m_{ev}. The thermo-physical properties of the humid air were determined for the mean temperature [T_i=(T_g+ T_e)/2] by using Equationa (17)-(21) as given in Appendix 1. Then these properties were used to evaluate the values of Grashof (Gr) and Prandtl (Pr) numbers. The values of the experimental constant (C and n) in the equation of Nu were calculated by simple regression analysis. Then the value of h_c from Equation (1) was determined hourly. Then, the value of h_c was used in the Equation (9) to evaluate the value of h_e.

3 Results and discussion

The experimental data collected for the drying of groundnut samples 1, 2, and 3 under free convection GHD condition are given in Table 1.

The data given in Table 1 were used to calculate the values of experimental constants C and n in the Nu equation by using simple linear regression analysis. The values of 'C' and 'n' were used in Equation (2) to determine the values of h_c. Then, the values of h_c were further used in the Equation (9) to evaluate the values of h_e. The values of greenhouse thermal efficiency (η_{gh}), energy efficiency (η_{En}), and exergy efficiency (η_{Ex}) were evaluated using Equation 10, 13, and 16 respectively. The values of various evaluated parameters (h_c, h_e, η_{gh}, η_{En}, and η_{Ex}) are summarised in Table 2. Parameters used for computation are given in Appendix 2.

It is observed from Table 1 that the evaporation of water vapour (m_{ev}) occurs at a faster rate during initial couple of hours but declines as the day progresses. The computed values of the experimental constants 'C' and 'n' were found to be 0.52 and 0.202, 0.99 and 0.10, and 0.90 and 0.113 for the drying of groundnut samples 1, 2, and 3 respectively. The values of h_c and h_e were observed to lie within 0.34 to 1.66 W m^{-2} ^{o}C^{-1} and 4.97 to 344.96 W m^{-2} ^{o}C^{-1} respectively for the drying of given groundnut samples. The values of h_c and h_e were found to decrease with the increase in size of wire mesh sieve. These results are found in accordance with those reported in the literature for FCGHD of single layer groundnuts drying. The range of Grashof number (Gr) is also specified. The product of Gr and Prandtl (Pr) numbers (0.18×10^6 to 6.77×10^6) shows that the entire drying falls within the laminar region, i.e., GrPr≤10^7 (Sahdev et al., 2017b). The variation of h_c and h_e for groundnut samples 1, 2, and 3 with respect to time are shown in Figure 2(a) and 2(b) respectively. The photographs of groundnut samples are shown in Figure 3.

Table 1 Experimental data for free convection drying of groundnut samples

Time	T_g (°C)	T_e (°C)	m_{ev} ×10^{-3} (kg)	γ (%)	Gr ×10^6	Pr	$\sum(I_i \times A_i)\times\tau$ (W m^{-2})
Sample 1 (13 April, 2016)							
7-8 am	27.9	31.65	9.8	38.19	9.70	0.698	44.59
8-9 am	34.6	38.31	13.6	28.64	8.56	0.697	53.31
9-10 am	40.5	44.91	14.7	24.81	5.99	0.696	59.54
10-11 am	45.5	48.75	13.5	17.73	3.48	0.695	60.87
11-12 noon	49.1	49.64	8.6	9.47	1.56	0.695	59.69
12-1 pm	53.0	51.46	5.7	8.14	1.68	0.695	59.10
1-2 pm	55.7	53.31	4.5	7.09	0.26	0.694	54.63
2-3 pm	53.5	51.73	2.1	7.30	0.36	0.694	49.91
Sample 2 (14 April, 2016)							
7-8 am	30.8	33.10	23.5	38.59	3.21	0.697	114.99
8-9 am	38.8	39.15	32.4	26.79	2.38	0.696	150.04
9-10 am	48.3	47.68	29.1	15.94	0.61	0.695	177.50
10-11 am	58.7	53.86	27.4	8.76	1.68	0.694	173.41
11-12 noon	62.8	53.63	18.3	7.45	2.93	0.694	173.52
12-1 pm	64.1	53.46	10.1	6.41	3.18	0.694	182.51
1-2 pm	65.1	55.83	11.5	4.68	2.49	0.693	171.62
2-3 pm	63.9	56.77	6.4	4.31	2.58	0.693	120.88
3-4 pm	59.6	54.68	5.8	5.23	2.04	0.694	98.65
4-5 pm	51.7	49.29	5.1	7.66	1.89	0.695	53.60
5-6 pm	44.0	42.91	1.9	11.07	0.76	0.696	17.21
Sample 3 (15 April, 2016)							
7-8 am	29.6	32.38	35.7	39.49	9.43	0.698	205.71
8-9 am	36.7	37.36	75.0	23.26	7.37	0.697	247.35
9-10 am	45.9	43.37	64.4	16.65	4.53	0.696	335.04
10-11 am	55.5	50.99	51.8	10.50	1.71	0.694	363.73
11-12 noon	61.1	54.14	37.8	4.19	5.82	0.694	353.79
12-1 pm	64.1	55.72	25.0	2.48	6.03	0.694	298.51
1-2 pm	63.9	56.72	17.0	1.90	6.39	0.693	286.32
2-3 pm	59.2	53.80	13.0	2.61	7.07	0.694	241.42
3-4 pm	55.3	51.43	8.0	2.84	4.25	0.694	214.53
4-5 pm	52.2	50.60	6.7	2.79	3.39	0.695	133.19
5-6 pm	47.2	46.31	6.3	5.07	3.32	0.695	60.62

Table 2 Values of various evaluated parameters

Constants, convective and evaporative heat transfer coefficients						
Sample	C	n	h_c (W m^{-2} ^{o}C^{-1})	$h_{c,avg}$ (W m^{-2} ^{o}C^{-1})	h_e (W m^{-2} ^{o}C^{-1})	$h_{e,avg}$ (W m^{-2} ^{o}C^{-1})
1	0.52	0.202	0.86-1.66	1.32	14.10-344.96	103.88
2	0.99	0.10	0.39-0.48	0.45	7.69-103.39	37.52
3	0.90	0.113	0.34-0.40	0.39	4.97-63.04	29.75
Thermal, energy, and exergy efficiencies of greenhouse dryer						
Sample	η_{gh} (%)	$\eta_{gh,avg}$ (%)	H_{En} (%)	$H_{En,avg}$ (%)	H_{Ex} (%)	$H_{Ex,avg}$ (%)
1	2.77-17.06	10.87	9.31-17.03	13.86	1.78-8.28	5.22
2	3.46-13.73	7.74	11.82-31.30	21.55	0.04-3.89	1.59
3	2.45-20.26	7.87	14.43-71.44	32.61	0.16-4.73	1.45

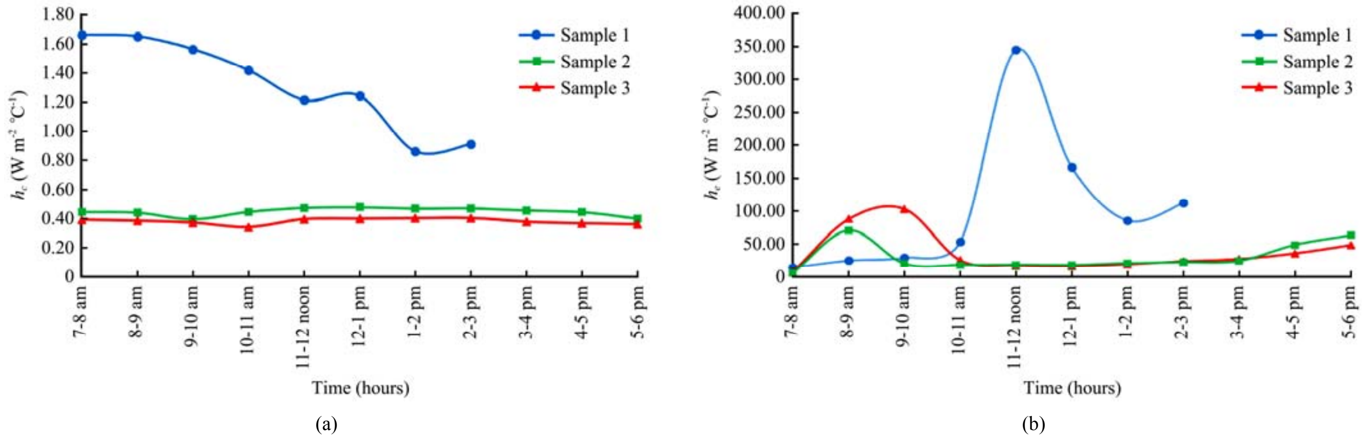


Figure 2 Variation in h_c, and h_e with time for free convection groundnut GHD

The values of η_{gh}, η_{En}, and η_{Ex} for the free convection greenhouse dryer were observed to vary from 2.45%-20.26%, 9.31%-71.44%, and 0.04%-8.28% respectively. The overall average values of η_{gh}, η_{En}, and η_{Ex} were evaluated to be 8.83%, 22.67%, and 2.75% respectively.

The computed values of experimental error (Appendix 3) in terms of % uncertainty, i.e., internal uncertainty (IU) and external uncertainty (EU) are given as: (a) Sample 1 = 27.78% (IU) + 1.5% (EU) = 29.28%, (b) Sample 2 = 38.64% (IU) + 1.5% (EU) = 40.14%, and (c) Sample 3 = 42.91% (IU) + 1.5% (EU) = 44.41%. The overall average experimental error in terms of % uncertainty is evaluated as 37.94%.

The error bars (95% CI) which depicts the variability of h_c and h_e from its true value are presented in Figure 4. Statistical Package for Social Sciences (SPSS) software (version 24) is used to draw the error bars.

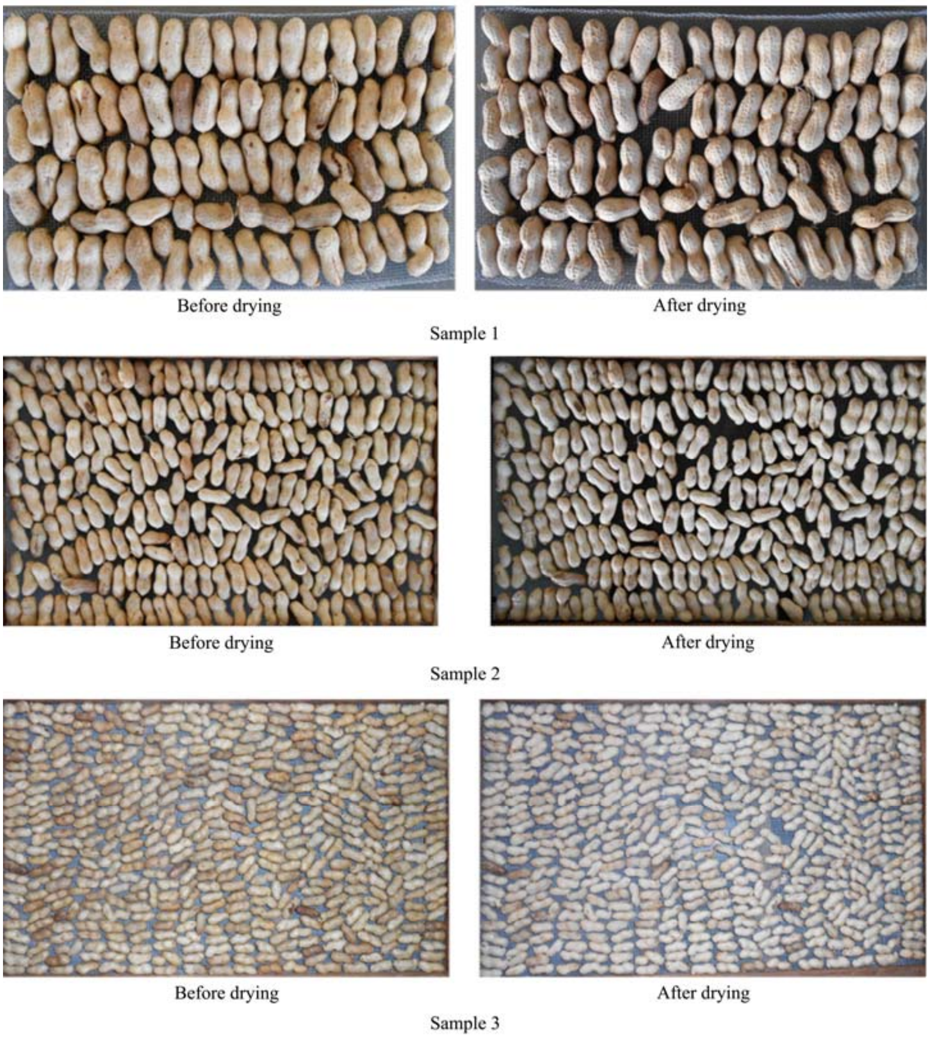


Figure 3 Photograph of groundnut samples 1, 2, and 3 before and after drying

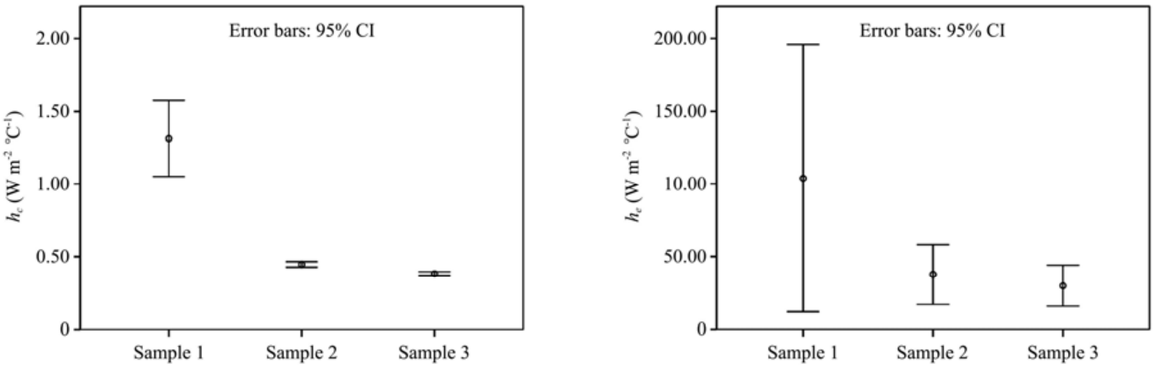


Figure 4 Error bars for h_c and h_e

4 Conclusions

In this research work, the effect of wire mesh sizes on h_c and h_e for groundnut drying inside a free convection greenhouse were investigated which would be supportive in designing a better groundnut dryer. The following conclusions have been drawn.

(1) The average values of h_c for groundnut drying of samples 1, 2, and 3 under free convection GHD mode were observed to be 1.32, 0.45, and 0.39 W m^{-2} ^{o}C^{-1} respectively. And the corresponding values of h_e for drying of samples 1, 2, and 3 were found to be 103.88, 37.52, and 29.75 W m^{-2} ^{o}C^{-1} respectively.

(2) The values of h_c and h_e were observed to decrease with the increase in sieve size for the drying of groundnuts under free convection GHD mode.

(3) The overall average greenhouse thermal efficiency, energy efficiency and exergy efficiency for groundnut drying was found to be 8.83%, 22.67%, and 2.75% respectively.

(4) The overall average experimental error in terms of % uncertainty for given samples was computed as 37.94%.

Acknowledgement

Authors are thankful to Maharshi Dayanand University, Rohtak, India, and Guru Jambheshwar University of Sciences & Technology, Hisar, India for providing the laboratory and internet facilities.

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Appendix 1

Physical properties of the humid air

The thermo-physical properties of the humid air were calculated for T_i by using the following Equation (17)-(21) (Kumar, 2016):

$$K_v=0.0244+0.7673\times10^{-4}T_i \quad (17)$$

$$\mu_v=1.1718\times10^{-5}+4.620\times10^{-8}T_i \quad (18)$$

$$C_v=999.2+0.1434T_i+1.101\times10^{-4}T_i^2-6.7581\times10^{-8}T_i^3 \quad (19)$$

$$\rho_v=353.44/(T_i+273.15) \quad (20)$$

$$\mathrm{P(T)}=e^{[25.317-5144/(T+273.15)]} \quad (21)$$

Appendix 2

Various computational parameters

$\tau=0.9$; $\alpha_g=0.4$; $\alpha_{gnd}=0.2$; $A_0=0.9225$ m^2 (Sample 1); A_0=0.86 m^2 (Sample 2); A_0=0.75 m^2 (sample 3); N_{ap}=10; V_{gh}=0.53 m^3; and T_{sun}=6000 K

Appendix 3

Experimental error

The experimental errors were determined in terms of % uncertainty i.e., internal uncertainty (IU) and external uncertainty (EU) for the water vapour evaporated. The equations used to calculate internal uncertainty are as (Sahdev et al., 2017a):

$$U'=\sqrt{\sigma_1^2+\sigma_2^2+...+\sigma_n^2}\ /\ N \quad (22)$$

where, σ (i.e., standard deviation) is given as:

$$\sigma=\sqrt{\sum(X_i-\overline{X_i})\ /\ N_0} \quad (23)$$

where, X_i = water vapour evaporated and $(X_i-\overline{X_i})$ = The deviation of the observations from the mean value.

N = The number of sets, and N_0 = number of observations in each set. The % uncertainty was evaluated as:

$$\%\ \mathrm{IU} = (U'\ /\ \text{Mean of total number of observations})\times100 \quad (24)$$

Nomenclature

A_i = Area of greenhouse wall in m^2

A_o = Area inside greenhouse other than sieve in m^2

C_a = Specific heat of the drying air in J kg^{-1} ^{o}C^{-1}

C_v = Specific heat of the humid air in J kg^{-1} ^{o}C^{-1}

g = Acceleration due to gravity in m s^{-2}

Gr = Grashof number = $g\beta X^3\rho^2\Delta T\,\mu^{-2}$

$h_{c,avg}$ = Average convective heat transfer coefficient in W m^{-2} ^{o}C^{-1}

$h_{e,avg}$ = Average evaporative heat transfer coefficient in W m^{-2} ^{o}C^{-1}

I_i = Solar radiations on the greenhouse wall in W m^{-2}

I_v = Thermal conductivity of the humid air in W m^{-1} ^{o}C^{-1}

M_{ao} = Mass flow rate of drying air at outlet of greenhouse dryer in kg s^{-1}

n = Experimental constant

N_{ap} = Number of air passes

Nu = Nusselt number = h_cX_d/K_v

Pr = Prandtl number = $\mu C_p/K_v$

$P(T)$ = Partial vapour pressure at temperature T in N m^{-2}

T_s = Sun temperature = 6000 K

T_v = Vent temperature in ^{o}C

ΔT = Effective temperature difference in ^{o}C

V_{gh} = Volume of greenhouse in m^3

X_d = Characteristics dimension in m

Greek symbols

α_g = Absorptivity of the groundnut

α_{gnd} = Absorptivity of ground inside the greenhouse

β = Coefficient of volumetric expansion in K^{-1}

γ = Relative humidity in %

μ_v = Dynamic viscosity of the humid air in N s m^{-2}

ρ_v = Density of the humid air in kg m^{-3}

η_{En} = Energy efficiency in %

$\eta_{En,avg}$ = Average energy efficiency in %

η_{Ex} = Exergy efficiency in %

$\eta_{Ex,avg}$ = Average exergy efficiency in %

η_{gh} = Greenhouse thermal efficiency in %

$\eta_{gh,avg}$ = Average greenhouse thermal efficiency in %

τ = Transitivity of the greenhouse covering material

Abbreviations used

CI = Confidence interval

OSD = Open sun drying

GHD = Greenhouse drying

IU = Internal uncertainty

EU = External uncertainty

NCGHD = Natural convection greenhouse drying

FCGHD = Forced convection greenhouse drying