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INVESTIGATION OF INDIRECT SOLAR DRYING OF GINGER RHIZOMES (ZINGIBER OFFICINALE): A COMPARATIVE STUDY

SUNIL K. SANSANIWAL[1,*], M. KUMAR[2], RAJNEESH[3], V. KUMAR[2]

[1]Centre for Energy and Environment, Malaviya National Institute of Technology (NIT), Jaipur 302017, India
[2] Mechanical Engineering Department, Guru Jambheshwar University of Science & Technology, Hisar 125001, India
[3]Mechanical Engineering Department, National Institute of Technology (NIT), Kurukshetra 136119, India
*Corresponding author: sansaniwal@gmail.com

Abstract

In this communication, an attempt has been made to investigate the drying kinetics of ginger rhizomes under natural and forced convection indirect solar drying modes. Various experiments were conducted during the months of March and April 2014 in the climate conditions of Hisar (29°5'5''N, 75°45'55''E), India. The data thus obtained for natural and forced convection drying modes was used to determine the constants 'C' and 'n' in the Nusselt number expression through linear regression analysis. Based on the values of these constants, the convective heat transfer coefficients for natural and forced convection drying modes were evaluated and reported to vary from 0.59 to 5.42 W/m^2°C and 2.52 to 6.33 W/m^2°C, respectively. As compared to the natural convection drying mode, the average collector efficiency and moisture removing rates were obtained to be higher under forced convection drying mode. Further, the experimental errors in terms of percent uncertainty were also determined.

Keywords: Solar drying, Indirect solar dryer, Ginger drying, Natural and forced convection heat transfer, Convective heat transfer coefficient, Moisture removing rate.

1. Introduction

Ginger (Zingiber officinale) is an important edible spice extensively grown worldwide. It is believed to be a native economic crop of South East Asia. India is the largest ginger producing country in the world. The ginger has many medicinal properties and thus widely used in Ayurveda and cooking applications. The ginger mainly consists of fibrous content, volatile oil and non-volatile ether extract. It is consumed as green ginger, dried ginger and in powder form. The drying of ginger is an important practice for self-life enhancement and preservation and thus it is

Nomenclatures

$A_{o,c}$	Area of collector outlet, m^2
A_t	Area of the tray, m^2
C	Constant
c_v	Specific heat, J/kg°C
Gr	Grashof number
h_c	Convective heat transfer coefficient, W/m^2°C
$h_{c,avg}$	Average convective heat transfer coefficient, W/m^2°C
I	Solar irradiation, W/m^2
K_v	Thermal conductivity, W/m°C
$M_{exp,i}$	Experimental moisture ratio
$M_{initial}$	Initial moisture removing rate, % dry basis
$M_{pre,i}$	Predicted moisture ratio
n	Number of drying model constants, constant
N	Number of observations
N_o	Number of sets
Nu	Nusselt number
$P(T)$	Partial vapour pressure at temperature T, N/m^2
Pr	Prandtl number
Q_e	Rate of heat utilized to evaporate moisture, J/m^{2}s
Q_i	Heat input, J/s
Q_o	Heat output, J/s
Re	Reynolds number
RH	Relative humidity
RTD	Resistance temperature detector
t	Time interval, s
T_c	Product temperature, °C
T_e	Product surrounding temperature, °C
$T_{i,c}$	Temperature at collector inlet, °C
$T_{i,c}$	Temperature at dryer inlet, °C
$T_{o,c}$	Temperature at collector outlet, °C
$T_{o,d}$	Temperature at dryer outlet, °C
T_s	Average surface temperature of absorber plate, °C
V_i	Average air velocity at collector inlet, m/s
V_o	Average air velocity at collector outlet, m/s
W_d	Weight of dry ginger, g
W_w	Weight of wet ginger, g
X	Characteristics length, m

Greek Symbols

δ	Standard deviation
η_c	Collector efficiency, %
λ	Latent heat of vaporization, kJ
μ_c	Dynamic viscosity, kg/m.s
ρ_v	Density of humid air, kg/m^3

frequently dried through the traditional methods like open sun drying. Open sun drying is a cheap and easy method of drying, however, this technique is suffering from various bottlenecks such as poor drying quality, larger drying time and the drying product is vulnerable to the environmental debris, rain, animals, etc. [1-3].

Various eminent researchers have developed various drying methods worldwide to explore the most effective method of drying. The forced convection solar drying is an emerging and widely used technique of product drying. It involves the application of a fan to force the air across the drying unit to enhance the specific moisture removing rate for efficient product drying [4]. The product quality obtained under forced convection indirect solar drying can meet the international market standards.

Many researchers have studied the drying characteristics of ginger rhizomes using various types of solar drying systems. Some of them are: Mani et al. [5] evaluated the convective heat transfer coefficient of ginger in open sun drying conditions under natural convection mode. The convective heat transfer coefficient of ginger was reported to be 26.3 W/m^2°C. Similar study Akpinar and Toraman [6] evaluated the convective heat transfer coefficient of ginger to be ranging from 0.3 to 2.1 W/m^2°C in a cyclone type convective dryer for air drying temperature of 40-70°C and air velocity of 0.8-3.0 m/s). The average moisture diffusivity and activation energy were also examined and obtained to be varied from 2.8×10^{-10} to 6.7×10^{-10} m^2/s and 13.3 to 22.7 kJ/mol respectively. Prasad et al. [2] experimentally studied the ginger drying and compared the results with solar hybrid dryer and open sun drying. The drying rate of hybrid dryer was reported to be higher than open sun drying. The overall drying efficiency of dryer was obtained to be 18% and 13% under summer and winter climatic conditions respectively.

Phoungchandang et al. [7] developed the tray dryer, heat pump dehumidified dryer and mixed mode solar dryer for ginger drying. The best quality of ginger was obtained in heat pump dehumidified dryer and mixed mode solar dryer at 40°C and 62.8°C respectively without any pre-treatment of product. The modified page model was reported best suitable for describing the drying behaviour of ginger. Phoungchandang and Saentaweesuk [8] studied the drying characteristics of ginger under tray and heat pump assisted dehumidifier incorporated with single and two stages drying. The two-stage heat pump dehumidifier reduced the drying time by 59.3% at 40°C. Rajagopal et al. [9] experimentally studied the solar drying of copra (Cocos nucifera) under forced convection drying mode and compared the results with natural convection solar drying. The moisture content was observed to be reduced from 52.3 to 8% for drying chamber temperature of 49-78°C under natural and forced convection drying modes.

Deshmukh et al. [10] investigated the drying characteristics of ginger in a mixed mode solar cabinet dryer and reduced its moisture from 621.5 to 12.2% (db). As compared to open sun drying, the solar cabinet dryer was observed better in several aspects of product quality, drying time and power requirement. The page model was reported to be most suitable to describe the drying kinetics of ginger. Tchaya et al. [11] designed a forced convection indirect solar dryer for three different airflow modes namely, licking mode, crossing mode and mixed mode. As compared to licking mode, the drying temperature in crossing mode was observed higher by 8°C. For each mode of airflow, the drying temperature obtained in drying chamber was reported to vary from 40 to 69°C on each tray. Amedorme et al. [12] designed a forced convection indirect solar dryer for drying Moringa leaves (Moringa olivera) and reduced its moisture from 80 to 10% (wb) with a drying efficiency of 25%.

Deshmukh et al. [13] investigated the drying kinetics of untreated ginger for different air temperatures (45-65°C) and at a constant air velocity of 1.8 m/s. The page model was found suitable best for describing the drying kinetics of ginger among various statistically evaluated models. Mehta et al. [14] presented the drying performance of ginger inside a forced convection indirect solar dryer comprising a thermal storage for late evening drying. The moisture content of ginger was observed to be reduced from 84 to 9.63% in 36 hours with a dryer efficiency of 30%. Aggarwal [15] developed an indirect solar dryer incorporated with a solar cell for running fan and bulbs in collector unit for air heating during cloudy or night time drying of hill products. The drying potential and quality were found to be improved. Azimi et al. [16] studied the drying behaviour of eggplant (Solanum melongena) by using an indirect solar dryer. For both indirect and open sun drying, the midilli and kucuck model was reported better to study the drying kinetics of eggplant.

Loha et al. [17] developed a forced convection cabinet dryer for single layer ginger drying at different air-drying temperatures (45 to 60°C) and at a constant air velocity of 1.3 m/s. The moisture content of ginger was observed to be reduced from 87 to 6% (wb). Besides, the drying accuracy of different models was also determined by using non-linear regression method. Singh [18] studied a forced convection indirect solar dryer for drying silk cocoon. The moisture content was reduced from 60 to 12% (wb) at drying temperature of air varying from 50 to 75°C. In contrast of electrical oven drying, an electrical energy of 0.75 kWh/kg was saved. Further, the Wang and Singh model was validated in good agreement with the experimental data. Mohanraj and Chandrasekar [4] evaluated the drying performance of chili (Capsicum annuum) inside a forced convection indirect solar dryer integrated with different sensible heat storage material. The moisture content of chilli was observed to be reduced from 72.8 to 9.1% (wb) in 24 hours with dryer efficiency of 21% and specific moisture extraction rate of 0.87 kg/kWh.

Jain et al. [19] compared the drying performance of forced convection solar dryer with an electrically operated mechanical dryer for drying groundnut (Arachis hypogaea), ginger (Zingiber officinale) and garlic (Allium sativum). The cost-benefit ratios obtained for solar and mechanical dryers were reported to be 1.56 and 1.18 respectively. Kumar [20] evaluated the performance of a forced convection indirect solar dryer for ginger drying and obtained the convective heat transfer (3.95 W/m^2°C) and evaporative heat transfer coefficient (160.5 W/m^2°C). The average collector efficiency of the dryer was reported to be 14.5%. However, the experimental error in terms of percentage uncertainty was calculated to be 20.87%. Anum et al. [21] carried out the drying performance of onion (Allium cepa), ginger (Zingiber officinale) and cabbage (Brassica oleracea) inside a hybrid solar dryer (collector area 34% + drying area 64%). The moisture contents of onion (88.5 to 10.3%), ginger (55.8 to 15.7%) and cabbage (72.5 to 15.0%) were reduced in the drying time varying from 10 to 16 hours. Solar energy was observed to be capable of removing more than 70% moisture of the products. The overall efficiency of the dryer was obtained to be 42.8%.

Sansaniwal and Kumar [22] investigated the drying characteristics of ginger in terms of convective heat transfer coefficients and moisture removing rates, inside a natural convection indirect solar cabinet dryer. The average convective heat transfer coefficients were obtained to be varied from 0.59 to 5.42 W/m^2°C and reported to decrease with increase in mass of ginger samples and progression of drying days. However, the moisture removing rate was observed to increase with increase in mass of ginger samples while it was decreased with the progression of drying days. The average collector efficiency of dryer was calculated to be varied from 15.0 to 16.1%. The modified page model was reported suitable for describing the drying kinetics of ginger. Pandey et al. [23] developed a cabinet solar dryer operated under natural and forced convection modes for drying ginger at different air-drying temperatures (28 to 58°C) and flow rates (0.0378 to 0.0793 m^3/s). As compared to natural convection, the faster drying rates were observed in solar (using blower) and mixed drying (using blower and heater) modes.

The collector efficiency was calculated to be varied from 10 to 23%. Further, the same dryer was also used for chili (Capsicum annuum) drying. Borah et al. [24] compared the effect of drying on texture and colour characteristics of ginger (Zingiber officinale) and turmeric (Curcuma longa) in four different drying methods namely, integrated drying system (IDS), fluidized bed dryer (FBD), electrical oven (EO) and open sun drying (OSD). The minimum crushing strength of ginger (1124.6 g) was observed in IDS whereas the maximum value was obtained in OSD (1421.6 g). The colour loss values for ginger in IDS (34.8), FBD (38.1), EO (37.5) and OSD (32.2) were also obtained. On the other hand, the turmeric dried in IDS claimed maximum crushing strength (8789.0 g) while the minimum value was calculated for EO (6307.6 g). Similarly, the colour loss values for turmeric in IDS (52.7), FBD (61.0), EO (67.3) and OSD (58.2) were obtained. Among various drying methods, IDS was found best for product drying with quality texture and colour of different spices.

In the present study, an indirect solar dryer has been fabricated to study the drying characteristics of ginger under natural and forced convection drying modes in the meteorological conditions of Hisar (29°09’N, 75°42’E), India. The performance evaluation of solar drying system was carried out in terms of collector efficiency, moisture removing rates and convective heat transfer coefficients for different drying modes and drying time intervals.

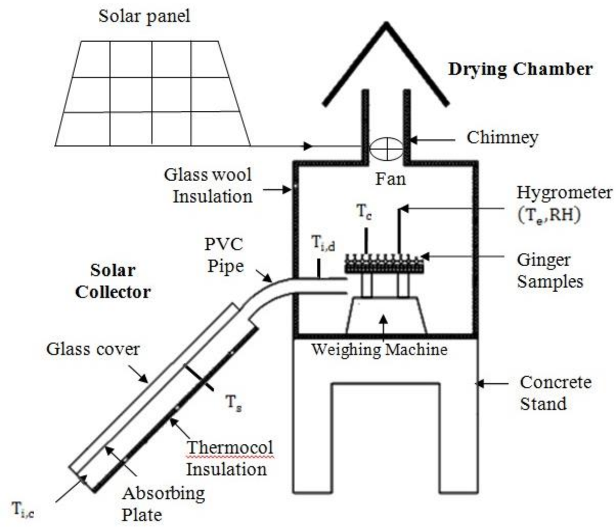
2. Material and methods

2.1. Experimental setup and instrumentation

The schematic and pictorial view of forced convection indirect solar dryer fabricated in the meteorological conditions of Hisar (29°09’N, 75°42’E), India is shown in Fig. 1. It was comprised of mainly two components namely, the flat plate collector and drying chamber. The collector unit having black coated absorber plate made of galvanized iron was used for air heating. A transparent glass sheet of thickness 8 mm was located over the collector to achieve the desired glazing effects attributed towards minimizing the thermal losses. Solar collector unit (1.3 m × 1 m) and drying chamber (0.41 m × 0.45 m × 0.53 m) were made thermally insulated with glass wool to minimize the energy losses. For forced convection drying mode, an induced fan (12 VDC) driven by the solar panel (1.195 m × 0.542 m × 0.034 m) was installed inside the dryer chimney (0.11 m × 0.11 m × 0.26 m) mounted at the top of the drying chamber. The fresh air was sucked in and got heated up inside the collector unit and then allowed to flow into the drying chamber through PVC pipe as shown in Fig. 1.

The accurately weighed ginger samples of initial moisture content 78% (db) were evenly distributed on the rectangular shaped wire mesh tray (0.11 m × 0.20

m). The heated drying air evaporated the moisture of given mass of ginger samples (i.e. 285 g). After predetermined time interval of 1 hour, the weight reduction of the product was recorded by using an electronic weighing balance (model TJ–6000, capacity 6 kg, least count of 0.1 g). A digital hygrometer (model HT-315) was located just above the product surface to monitor the relative humidity and product surrounding temperature. The temperature of drying air was measured by using resistance temperature detectors (PT-100 with accuracy ± 0.1°C) installed at different locations of collector unit and drying chamber as shown in Fig. 1. The velocity of fresh air at the inlet of collector unit was measured by using a digital anemometer (model AM-4201, least count 0.1 m/s). A digital solar power meter (model WACO-206, least readability ± 10 W/m^2) was used to measure the intensity of solar radiation during the drying days.



(a) Schematic view of indirect solar dryer.

(b) Pictorial view of indirect solar dryer.

Fig. 1. Schematic and pictorial view of indirect solar dryer [22].

2.2. Sample preparation

The fresh ginger was purchased from the local market of Hisar, India and washed thoroughly to remove the surface dust. The clean ginger was hand peeled by knife and shaped cylindrically with diameter 1.7 cm and length 3 cm. The samples were accommodated in a rectangular shaped wire mesh tray placed on the weighing balance. The initial moisture content of fresh ginger was determined by using hot air oven drying method [25].

2.3. Experimental procedure

The experimental observations were recorded between 9:00 am to 6:00 pm in the month of March and April 2014 at Guru Jambheshwar University of Science and Technology, Hisar (29°09'N, 75°42'E), India. A fixed size rectangular shaped wire mesh tray was used to accommodate the given mass of ginger samples (i.e. 285 g). The tray was kept on the digital electronic balance machine to determine the moisture removing rate (MRR) for each drying hour. A digital hygrometer was kept just above the surface of ginger samples facing its probe towards the sample surface. Every time, it was started one minute before recording the observations. The temperature was measured by using the calibrated RTD's installed at different locations in the drying system i.e. absorbing plate, dryer inlet, product surface and chimney inlet and outlet temperature. A digital anemometer was used to measure the volume flow rate of air at the collector and dryer inlet passage. The solar radiation data was collected by using the digital solar power meter. The experimental observations were recorded at every 1 hour time interval and the measurement was discontinued when the constant weight of ginger samples was achieved. The difference in weight of fresh (or wet) sample and dried sample directly gave the quantity of water evaporated during any drying time interval. The fresh and dried ginger samples are shown in Fig. 2.

Fig. 2. Fresh and dried ginger samples.

The data thus obtained from the measurements of ginger weight was used to study the drying kinetics of ginger in terms of moisture removing rate and convective heat transfer coefficient. The moisture removing rate was expressed on dry basis. Therefore, the initial moisture removing rate on % dry basis can be calculated by using Eq. (1) [22]:

$$M_{initial} = \frac{W_w - W_d}{W_d} \times 100 \tag{1}$$

3. Theoretical considerations

3.1. Thermal modelling

The convective heat transfer coefficients for evaporation were determined by using the following expression [26, 27]:

$$Nu = \frac{h_c X}{K_v} = C\left(Gr\ \Pr\right)^n \tag{2}$$

The rate of heat utilized to evaporate the moisture is given in the following forms [26, 27]:

$$Q_e = 0.016 h_c\left[P\left(T_c\right) - \lambda P\left(T_e\right)\right] \tag{3}$$

On substituting h_c from Eq. (2), Eq. (3) may be re-written as follows [26, 27]:

$$Q_e = 0.016\frac{K_v}{X}C\left(Gr\ \Pr\right)^n\left[P\left(T_c\right) - \lambda P\left(T_e\right)\right] \tag{4}$$

The moisture evaporated during drying can be determined by dividing Eq. (4) with the latent heat of vaporization (λ) and multiplying it with the area of tray (A_t) and drying time interval (t) given as follows [26, 27]:

$$m_{ev} = \frac{Q_e}{\lambda}\left(A_t\ t\right) = 0.016\frac{K_v}{\lambda X}C\left(Gr\ \Pr\right)^n\left[P\left(T_c\right) - \lambda P\left(T_e\right)\right]\left(A_t\ t\right) \tag{5}$$

Let,

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

Substitute the value of Z in Eq. (5) will give the following expression [26, 27]:

$$\frac{m_{ev}}{Z} = C\left(Gr\ \Pr\right)^n \tag{6}$$

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

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

This is in the form of a linear equation and may be analogous as [26, 27]:

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

where

$y = \ln\left[\frac{m_{ev}}{Z}\right]$, $m = n$ and $c = \ln C$

For natural convection analysis [26, 27]:

$$x = \ln\left(Gr\ \Pr\right)$$

and for forced convection analysis [26, 27]:

$$x = \ln\left(\mathrm{Re}\ \Pr\right)$$

The values of constant ‘n’ and ‘C’ in Eq. (8) were obtained by using the simple linear regression method given as follows [26, 27]:

$$m = \frac{N\sum X_0 Y - \sum X_0 \sum Y}{N\sum X_0^{\ 2} - \left(\sum X_0\right)^2} \tag{9}$$

and

$$c = \frac{\sum X_0^{\ 2}\sum Y - \sum X_0 \sum X_0 Y}{N\sum X_0^{\ 2} - \left(\sum X_0\right)^2} \tag{10}$$

3.2. Thermal properties of air

The physical properties of humid air were evaluated by using the following expressions [27]:

$$C_v = 999.2 + 0.143T_i + 1.101\times 10^{-4}T_i^2 - 6.7581\times 10^{-8}T_i^3 \tag{11}$$

$$K_v = 0.0244 + 0.7673\times 10^{-4}T_i \tag{12}$$

$$K_v = \frac{353.44}{T_i + 273.15} \tag{13}$$

$$\mu_v = 1.718\times 10^{-5} + 4.620\times 10^{-8}T_i \tag{14}$$

$$P(T) = \exp\left[25.317 - \frac{5144}{T_i + 273.15}\right] \tag{15}$$

where $T_i = \left(T_c + T_e\right)/2$

The physical properties of humid air were used to determine the values of Grashof number (Gr) and Prandtl number (Pr). Whereas the values of constants ‘C’ and ‘n’ used in Nusselt number expression were calculated by using the linear regression analysis. Based on the values of these constants, the values of convective heat transfer coefficient were evaluated from Eq. (2) at the increment of one hour of observation.

3.3. Solar flat plate collector efficiency

The heat gained by drying air or the total heat at the collector outlet is given by the following expression [28]:

$$Q_o = V_o \times A_{o,c} \times \rho_v \times \left(T_{o,c} - T_{i,c}\right)\times C_v \tag{16}$$

whereas the total amount of heat received by solar collector is given as follows [28]:

$$Q_i = I \times A_c \tag{17}$$

Therefore, the efficiency of solar flat plate collector can be determined by dividing Eqs. (16) and (17), i.e.,

$$\eta_c = \frac{Q_o}{Q_i} \tag{18}$$

3.4. Experimental error

The experimental errors were also determined in terms of percent uncertainty for the mass evaporated during the drying process. So, the internal uncertainty was calculated by using the following expressions [29]:

$$\%\ \text{uncertainity} = \left(\text{U/mean of the total observations}\right)\times 100 \tag{19}$$

where

$$U = \frac{\sqrt{\delta_1^{\,2}+\delta_2^{\,2}+\ldots\ldots+\delta_N^{\,2}}}{N_o} \tag{20}$$

4. Result and discussion

The given mass of ginger samples having the cylindrical shape (diameter 1.7 cm, length 3 cm) was dried under natural and forced convection drying mode. The drying tests of given mass of ginger samples were run by using a fixed size wire mesh tray of rectangular shape. The collector efficiency, moisture removing rate (%, db) and convective heat transfer coefficients were evaluated for the given mass of ginger samples under natural and forced convection drying modes as given in Table 1 to 5.

Table 1. Observations for natural convection indirect solar drying of given mass of ginger samples on first day of drying.

Time	T_s	$T_{i,c}$	$T_{o,c}$	I	η_c	T_c	T_e	Mass (g)	M_{evp} (g)	h_c (W/m^2°C)
09:00	36.4	23.6	30.8	401	-	24.9	25.34	309.2	-	-
10:00	51.9	26.7	49.3	497	11.19	31.95	31.63	300.2	9.0	5.54
11:00	63.2	31.6	57.1	545	13.51	34.65	35.84	286.1	14.1	5.65
12:00	68.3	32.8	65.7	580	15.99	40.50	42.31	271.1	15.0	4.37
13:00	71.9	34.8	68.2	603	15.68	42.60	44.31	253.9	17.2	5.63
14:00	72.0	35.7	67.9	588	15.77	43.35	45.16	238.5	15.4	5.64
15:00	69.3	36.3	65.5	530	15.33	43.70	45.52	221.1	17.4	5.88
16:00	61.5	35.6	59.1	470	14.55	42.25	43.90	205.1	16.0	5.85
17:00	49.1	33.1	48.6	280	13.58	37.85	39.21	193.3	11.8	5.28
18:00	41.0	31.5	38.8	65	13.12	34.70	35.52	185.4	7.9	4.95

Table 2. Observations for natural convection indirect solar drying of given mass of ginger samples on second day of drying.

Time	T_s	$T_{i,c}$	$T_{o,c}$	I	η_c	T_c	T_e	Mass (g)	M_{evp} (g)	h_c (W/m^2°C)
09:00	37.6	28.1	34.7	413	-	27.2	27.91	192.6	-	-
10:00	55.0	31.1	52.8	502	13.69	33.95	34.13	177.6	15.0	3.53
11:00	68.3	33.1	65.0	590	16.49	39.55	40.50	166.8	10.8	3.62
12:00	74.9	38.4	71.0	602	16.22	43.2	43.85	154.0	12.8	3.61
13:00	72.6	38.8	72.0	590	16.96	45.1	45.30	136.5	17.5	3.49
14:00	70.6	39.2	70.9	552	17.41	46.15	45.88	122.8	13.7	3.37
15:00	64.3	38.5	66.1	490	17.37	45.55	45.11	109.0	13.8	3.21
16:00	57.5	37.5	58.4	401	16.39	42.8	42.49	100.6	8.4	3.09
17:00	47.4	35.2	49.0	299	14.95	39.6	39.29	95.8	4.8	2.91
18:00	37.5	34.7	37.4	68	13.25	34.7	34.65	92.5	3.3	2.76

Table 3. Observations for natural convection indirect solar drying of given mass of ginger samples on third day of drying.

Time	T_s	$T_{i,c}$	$T_{o,c}$	I	η_c	T_c	T_e	Mass (g)	M_{evp} (g)	h_c (W/m^2°C)
09:00	37.3	28.0	33.4	405	-	27.2	27.30	100.1	-	-
10:00	51.2	31.4	49.8	498	11.83	34.5	34.27	94.6	5.5	0.63
11:00	56.7	32.5	58.8	520	15.94	40.7	39.98	87.6	7.0	0.63
12:00	66.5	36.5	67.5	580	16.39	45.5	44.54	81.3	6.3	0.63
13:00	73.2	39.0	72.2	610	16.38	50.1	48.03	77.7	3.6	0.59
14:00	59.3	37.4	58.3	515	12.70	45.2	44.21	73.2	4.5	0.58
15:00	65.1	38.8	64.1	501	15.54	47.3	46.20	72.1	1.1	0.59
16:00	59.8	38.0	60.2	445	15.59	46.5	45.48	71.1	1.0	0.58
17:00	49.9	37.3	50.2	293	14.15	42.5	41.61	70.5	0.6	0.55
18:00	39.3	36.8	39.3	63	13.17	36.3	36.70	70.2	0.3	0.61

Table 4. Observations for forced convection indirect solar drying of given mass of ginger samples on first day of drying.

Time	T_s	$T_{i,c}$	$T_{o,c}$	I	η_c	T_c	T_e	Mass (g)	M_{evp} (g)	h_c (W/m^2°C)
09:00	38.2	28.8	31.1	417	-	25.4	25.28	311.2	-	-
10:00	52.3	32.3	48.6	501	20.78	33.4	33.78	293.9	17.3	6.61
11:00	64.7	33.6	59.0	540	28.99	37.8	38.09	274.3	19.6	6.61
12:00	68.2	35.7	66.5	591	31.81	41.8	42.05	241.8	32.5	6.12
13:00	71.7	38.4	69.8	620	30.62	44.8	44.68	217.1	24.7	6.12
14:00	72.1	39.1	69.6	598	30.79	46.2	45.80	189.2	27.9	6.12
15:00	68.8	38.7	64.4	525	29.83	44.7	43.97	167.1	22.1	6.12
16:00	61.8	37.2	59.1	470	28.95	40.6	39.95	153.4	13.7	6.12
17:00	49.8	36.1	47.2	297	24.04	38.2	37.56	143.3	10.1	6.61
18:00	41.2	35.7	38.1	69	22.96	35.5	35.63	135.3	8.0	6.61

Table 5. Observations for forced convection indirect solar drying of given mass of ginger samples on second day of drying.

Time	T_s	$T_{i,c}$	$T_{o,c}$	I	η_c	T_c	T_e	Mass (g)	M_{evp} (g)	h_c (W/m^2°C)
09:00	37.3	28.1	32.1	420	-	25.8	25.14	145.2	-	-
10:00	52.8	31.4	50.2	510	23.51	32.8	33.16	138.0	7.2	2.50
11:00	65.2	33.3	60.2	589	28.11	37.45	38.09	128.2	9.8	2.51
12:00	70.1	36.2	67.6	613	31.10	41.75	42.72	111.0	17.2	2.52
13:00	72.0	38.5	69.9	640	29.63	44.1	44.76	100.2	10.8	2.53
14:00	71.0	38.4	69.4	610	30.78	45.2	45.61	90.7	9.5	2.53
15:00	67.3	38.7	65.3	549	29.65	44.6	44.86	82.7	8.0	2.53
16:00	60.1	37.1	58.8	490	27.65	41.85	42.08	76.0	6.7	2.52
17:00	48.7	35.9	48.2	296	26.82	38.45	38.67	72.6	3.4	2.51
18:00	39.8	34.5	37.3	71	26.14	34.9	35.26	70.2	2.4	2.51

The data given in Table 1 to 5 was used to determine the collector efficiency, moisture removing rate and convective heat transfer coefficients for the given mass of ginger samples under natural and forced convection drying modes for the drying time interval of 1 hour on different days of drying as shown in Figs. 3 to 5. The efficiency of solar flat plate collector is a measure of air heating capability during the drying time. It highly depends on the velocity of air passing through the collector unit. When the ambient air make contact with hot absorber plate, it gets heated up and losses its density. Thus, the air flow in natural convection drying mode takes place due to the buoyancy effects.

On the other hand, in forced convection drying mode, an external aid is required to push the air inside the collector unit for faster heating of air. This can be achieved by using either a blower at the collector inlet passage or an induced fan at the collector outlet. In the present study, an induced fan was installed inside the dryer chimney mounted at the top of the drying chamber. As compared to natural convection drying mode, the efficiency of air heating in forced convection drying mode is observed more due to the laminar flow of air at constant speed. From Fig. 3, the collector efficiency obtained under forced convection drying mode is high and reported to lie in between 27.90 to 33.92% whereas it is observed less under natural convection drying mode and obtained to be ranging from 14.97 to 16.14%.

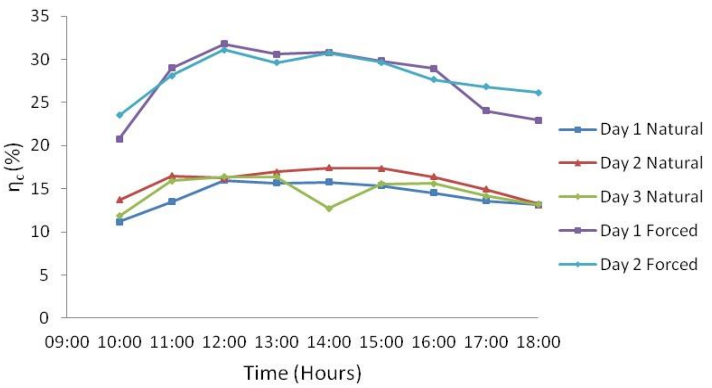


Fig. 3. Variations in the collector efficiency with respect to time under natural and forced convection indirect solar drying modes of given mass of ginger samples.

The moisture removing rate is the rate by which any product losses its water content during the drying time. It highly depends on the moisture present in the given mass of product along with the condition of drying air such as temperature, humidity, flow rate etc. In general, the moisture present in given mass of ginger samples exists in two forms namely, free moisture and bound moisture. The free moisture is present in the outer resins of ginger which can be easily evaporated by optimum heated air. Whereas the bound moisture takes place in the internal cells of ginger mass under capillary action which takes time for evaporation and leads to the higher drying time. For faster drying of given ginger mass, a high volume of heated air is required to evaporate the bound moisture [30, 31].

Therefore, the forced convection drying mode can fulfil such requirements of drying air and substantially reduces the product drying time. From Fig. 4, it can be observed that the forced convection drying of given mass of ginger samples completes in two days while the same process requires one additional day for its completion under natural convection drying mode. Further, it may also be concluded that the moisture removing rates during the initial drying days are more and decreases significantly with the progression of drying days (i.e. from first day of drying to next day of drying). This fact may be explained due to the attainment of equilibrium (or constant) weight by given mass of ginger samples at the completion of drying process.

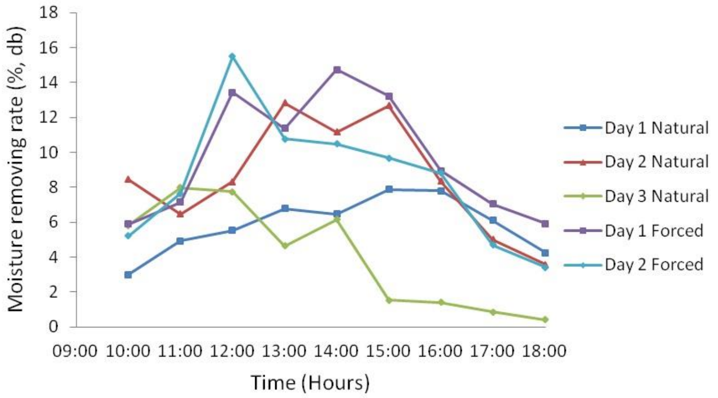


Fig. 4. Variations in moisture removing rate (%, db) with respect to time under natural and forced convection indirect solar drying modes of given mass of ginger samples.

From Fig. 5, it has been observed that the value of convective heat transfer coefficients decreases with the progression of drying days. This decrease is due to continuous reduction in the moisture removal rate from first day to next day of drying as discussed earlier in the previous section. Due to faster heating process, the values of convective heat transfer coefficients are reported higher under forced convection drying mode and observed to vary from 2.52 to 6.33 W/m^2°C against the variation of 0.59 to 5.42 W/m^2°C for natural convection drying mode. Further, the values of convective heat transfer coefficient are also observed to be depending on the mass of fresh ginger samples and presumed that the drying kinetics is highly dependent on the given mass of ginger samples.

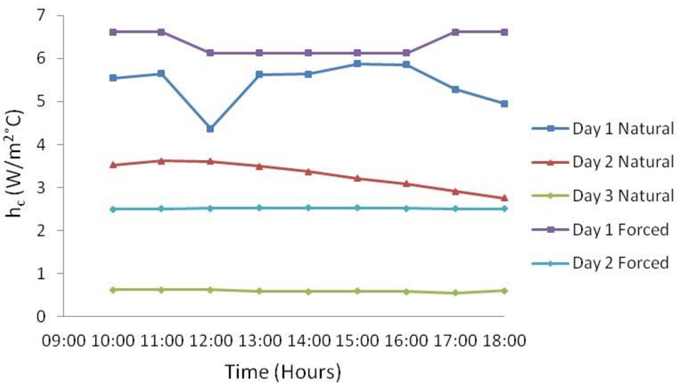


Fig. 5. Variations in convective heat transfer coefficients with respect to time under natural and forced convection indirect solar drying modes of given mass of ginger samples.

5. Conclusion

In the present study, an indirect solar dryer has been designed and developed to investigate the drying kinetics of ginger in terms of convective heat transfer coefficients, moisture removing rates and collector efficiency under natural and forced convection drying modes. The data obtained through the experimental observations was used to determine the constants 'C' and 'n' in Nusselt number expression using the simple linear regression analysis. Based on these constants, the convective heat transfer coefficients were evaluated and reported to be higher under forced convection drying mode. The convective heat transfer coefficients obtained under natural and forced convection drying modes were reported to vary from 0.59 to 5.42 $W/m^2 °C$ and 2.52 to 6.33 $W/m^2 °C$ respectively. Besides, the moisture removing rates were also obtained to be higher under forced convection drying mode which ultimately reduced the product drying time. Further, the average collector efficiency under natural convection drying mode was calculated to be varied from 14.97 to 16.14%. However, it was obtained to be higher in forced convection drying mode and found to lie in between 27.90 to 33.92%, respectively. Therefore, the forced convection drying method was recommended for the drying of products having high moisture contents and requires either immediate consumption or quick preservation. Moreover, the experimental errors evaluated for the present study were found to be 29.19 - 46.25%. This research work would be useful in the optimum designing of solar dryers for drying of various products such as vegetables, fruits, crops, herbals etc.

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