DRYING OF CARROT SLICES IN A TRIPLE PASS SOLAR DRYER

by

***Kesavan SESHACHALAM*[a*], *Arjunan THOTTIPALAYAM VELLIANGIRI*[b], *and Vijayan SELVARAJ*[b]**

[a] Department of Mechanical Engineering, DDCSM Polytechnic College, Palacode, India
[b] Department of Mechanical Engineering, Coimbatore Institute of Engineering and Technology, Coimbatore, India

Original scientific paper
https://doi.org/10.2298/TSCI17S2389S

An indirect triple pass forced convection solar dryer was developed and its performance was evaluated for drying of carrot slices. The drying experiments were carried out under the meteorological conditions of Coimbatore city in India during the year 2016. The experimental set-up consists of a blower, triple pass packed bed air collector (using sand) with wire mesh absorber plate, and a drying chamber. The air mass flow rate was optimized to 0.062 kg/s. The initial moisture content of the carrot slices was reduced from 87.5% (on wet basis) to the final moisture content of 10% (wet basis) in 6 h duration. The thin layer drying characteristics were analyzed using twelve mathematical models available in open literature. The results showed that the pick-up efficiency of the dryer was varied in the range between 14 and 43% with an average air collector thermal efficiency of 44% during the experimentation. The drying characteristics of carrot slices was predicted with good degree of accuracy using Wang and Singh drying model.

Key words: *triple pass solar dryer, drying models, carrot drying*

Introduction

Thermal drying is an energy intensive processes of removing the moisture content from the agricultural materials due to the use of high grade energy (electricity) for producing hot air. Use of solar energy for producing hot air is an energy efficient option used for drying of agricultural materials. During last decade, many research and developments have been reported with solar dryers [1]. The common conclusion of the reported investigations confirmed that solar dryers are producing the high-quality products using renewable energy sources. Presently, the research and developments with solar dryer are focusing on the performance improvements of solar dryers for food processing [2]. In a related investigation, Aboul-Enein *et al.* [3] improved the performance of a forced convection solar dryer using sand and granite for drying applications. In another work, Jain [4] enhanced the performance of a solar dryer by integrating it with heat storage medium for different crops. Similarly, El-Sebaii *et al.* [5] investigated the year-round performance of a double pass forced convection solar air heater using iron scraps packed bed absorber plate. The performance was improved by about 25% when compared to the convenctional flat absorber plate. Mohanraj and Chandrasekar [6] reported that performance of a forced convection solar dryer was significantly improved by using packed bed solar air collectors. Aldabbagh *et al.* [7] investigated the performance of a single and double pass solar air

* Corresponding author, e-mail: sk7mch@gmail.com

heater (using wire mesh packed bed configuration) and reported that the performance was improved by about 45 and 84%, respectively. In another work, the performance of a double pass forced convection solar air heater using wire mesh absorber plate was improved by about 15% when compared to the single pass solar air heater [8]. Banout *et al.* [9] compared the drying characteristics of red chili in a double pass forced convection solar dryer and concluded that this type of solar dryer is an economical and technically feasible option for drying the red chilies. Similarly, many researchers established drying correlations for predicting the drying behavior of various agriculture materials [10-15]. The cited literature confirmed that many researchers have investigated the performance of forced convection solar dryers for processing different agriculture materials. However, the possibility of using triple pass forced convection solar dryer using heat storage is reported in open literature. Hence, an attempt has been made in this research work to explore the possibility of using triple pass forced convection solar dryer using wire mesh integrated absorber plate with packed bed configuration. The performance of the dryer was evaluated for processing carrot slices. The drying characteristics in the dryer was evaluated using twelve drying models and compared. Based on the prediction capability, the suitable drying model has been selected for predicting the drying characteristics of carrot.

Materials and methods

The triple pass forced convection solar dryer with wire mesh and packed bed absorber plate configuration was developed and evaluated its performance under the climatic conditions of Coimbatore (latitude 11.0183° N; longitude 76. 9725° E) during the year 2016.

Experimental set-up

The schematic representation of a triple pass forced convection solar dryer is shown in fig. 1. The experimental set-up consists of a blower of 560 W power capacity, triple pass flat plate solar air collector (2 × 1 m), and a drying chamber (1.5 × 1 × 1 m). The wire mesh is placed in the path of air flow for increasing the rate of heat absorption. The solar air collector has two transparent glass plates with 4 mm thickness. In addition, the dryer can hold granular sensible heat storage materials in the packed bed of volume 1.97 × 0.97 × 0.05 m. The three passes in the solar air collector are: between first and second glass, between the second glass and the top surface of sensible storage bed, and bottom surface of sensible storage bed and inside bottom surface of collector. The absorber plate and wire meshes are coated with black paint to increase the rate of heat absorption. The air passes between two glasses as first pass, then passes through the absorber and glass, finally the air flows below the packed bed as third pass. The packed bed is filled with a sand with grain size of 2 mm and specific heat capacity of 830 J/kg °C. Sand can absorb and retain the thermal energy during peak sunshine hours and release during off sunshine and during fluctuations in sunshine hours. The solar flat plate air collector was tilted to 11° facing south to increase the rate of heat absorption according to the latitude of the location. The bottom side of the solar air collector and sides of the air collector are insulated with glass wool of thickness of 50 mm thickness to reduce heat losses. The divergent and convergent sections are provided at the entry and exit of the solar air collector. The divergent portion was connected to a blower and the convergent portion was connected to a drying chamber. The drying chamber is having three trays with perforation of 95% porosity for holding the products to be dried.

Instrumentation

The solar irradiation was measured by solar power meter with an accuracy of ±10 W/m^2. The temperature at typical locations are measured using K-type thermocouples

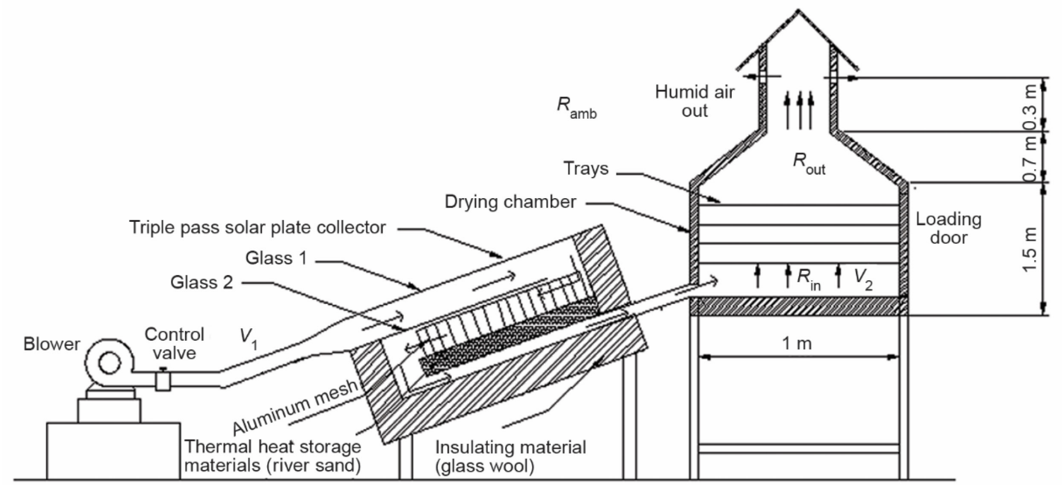

Figure 1. Schematic diagram of the experimental set-up; *V_1 – velocity of air at collector entry, V_2 – velocity of air at tray entry, R_{amb} – relative humidity of ambient air, R_{in} – relative humidity of air at drying chamber inlet, R_{out} – relative humidity of air at drying chamber outlet*

with an accuracy of ±0.5 °C. All the thermocouples are connected to a digital temperature indication of 0.1 °C resolution. Ambient wind velocity was measured by a digital anemometer with an accuracy of 0.1 m/s. The relative humidity of the air was measured by thermo-hygrometer using a probe with digital display having an accuracy of ±2%. The weight of the samples was measured by electronic weighing machine with an accuracy of 0.01 kg. The air mass flow rate was measured by a U-tube manometer connected with an orifice-meter placed in the path of air flow. The pressure drop across the solar collector was measured using an inclined (30° with horizontal) tube manometer having 0.5 mm least count and scale of 0-50 mm connected between the inlet and outlet of solar air collector.

Experimental procedure

The selected good quality carrots were sliced with 5 mm thick washed using boiling water at 90 ± 2 °C for the period of 5 minutes. The washed carrot samples were cooled immediately to room temperature. The pre-treated carrot slices were loaded over the trays of the drying chamber. The air velocity over the trays was adjusted to an optimum value 0.062 kg/s. Three trial experiments were carried out with similar ambient conditions to confirm the consistency in drying characteristics of carrot samples. All the experimental observations and drying characteristics were monitored for investigating the performance and drying characteristics.

Uncertainty analysis

The uncertainties in measuring temperature, air mass flow rate, humidity, and weight of the samples were determined using following equation:

$$w_r = \sqrt{\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2} \tag{1}$$

where R is a given function in terms of the independent variables. Let w_r be the uncertainty in the result and $w_1, w_2, \ldots, w_n$ be the uncertainties in the independent variables. The result R is a given function of the independent variables $x_1, x_2, x_3, \ldots, x_n$. The uncertainties in useful heat gain of collector, collector efficiency and the moisture ratio are ±0.199%, ±0.199%, and ±0.141%, respectively.

Data analysis

The equations used for predicting the drying characteristics of carrot slices in a triple pass solar dryer and the energy performance of a solar dryer are described in this section.

Drying characteristics

The initial moisture content was estimated by selecting five randomly selected samples with mass of 10 ± 1 g. These samples are kept in a convective oven by maintaining the temperature around 105 °C for the period of about four hours. The initial and final mass of the samples were measured using electronic balance with an accuracy of 0.01 g. The moisture content on wet basis was estimated by following equation:

$$M_{\mathrm{wb}} = \frac{m_{\mathrm{i}} - m_{\mathrm{f}}}{m_{\mathrm{i}}} \tag{2}$$

The rate of drying was estimated by:

$$DR = \frac{\mathrm{d}M}{\mathrm{d}t} = -k(M_{\mathrm{t}} - M_{\mathrm{e}}) \tag{3}$$

The moisture ratio is evaluated using the relation:

$$MR = \frac{M - M_{\mathrm{e}}}{M_{\mathrm{i}} - M_{\mathrm{e}}} \tag{4}$$

The equilibrium moisture content of the product is the safe level up to which the moisture can be removed. Table 1 shows different drying models used for predicting the drying characteristics of carrot slices [13].

The coefficients of each drying model were predicted based on the experimental trials. The accuracy of the model was predicted using reduced chi-square (χ^2) and root mean square error (RMSE). It is given by the equations:

$$\chi^2 = \sum_{i=1}^{i=N} \frac{(MR_{\mathrm{exp,i}} - MR_{\mathrm{pre,i}})^2}{N - n} \tag{5}$$

$$RMSE = \sqrt{\sum_{i=1}^{i=N} \frac{(MR_{\mathrm{exp,i}} - MR_{\mathrm{pre,i}})^2}{N}} \tag{6}$$

where $MR_{\mathrm{exp,i}}$ is the experimentally predicted moisture ratio, $MR_{\mathrm{pre,i}}$ – the predicted moisture ratio, N – the number of observations, and n – the number of a model's constants.

Dryer performance

The dryer performance was evaluated in terms of dryer thermal efficiency and its pick-up efficiency. The dryer thermal efficiency was estimated using following equation:

$$\eta_{\text{the}} = \frac{\dot{m}_a\ c_p(T_o - T_i)}{A_c\ I} \tag{7}$$

Table 1. Mathematical models applied to the drying curves

No.	Model name	Model
1	Newton	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified page	$MR = \exp[-(kt)^n]$
4	Henderson and Pabis	$MR = a\exp(-kt)$
5	Logarithmic	$MR = a\exp(-kt) + c$
6	Two term	$MR = a\exp(-k_0t) + b\exp(-k_1t)$
7	Two term exponential	$MR = a\exp(-kt) + (1 - a)\exp(-kat)$
8	Diffusion approach	$MR = a\exp(-kt) + (1 - a)\exp(-kbt)$
9	Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$
10	Verma *et al.*	$MR = a\exp(-kt) + (1 - a)\exp(-gt)$
11	Wang and Singh	$MR = 1 + at + bt^2$
12	Midilli and Kucuk	$MR = a\exp(-kt^n) + bt$

The pick-up efficiency was evaluated to determine the capacity of the dryer [15]. The dryer pick-up efficiency and specific moisture extraction rate (SMER) are evaluated using the equations:

$$\eta_{\text{p}} = \frac{W_o - W_t}{\dot{m}_a t(H_{\text{s}} - H_{\text{i}})} \tag{8}$$

where W_o [kg] is the weight of sample at t = 0, W_t [kg] – the weight of sample at any time t, $\dot{m}_{\text{a}}$ [kgs^{-1}] – the mass flow rate of air, t [hour] – the time, H_{s} [kg per water per kg of dry air] – the adiabatic saturation humidity of air entering the chamber, H_{i} [kg per water per kg of dry air] – the absolute humidity of air entering the chamber.

$$SMER = \frac{m_{\text{evap}}}{E_{\text{abs}}} \tag{9}$$

The pressure drop across the triple pass solar air collector is calculated by:

$$\Delta p = \rho g l \sin\theta \tag{10}$$

where ΔP [Nm^{-2}] is the pressure drop, ρ [kgm^{-3}] – the density of the manometer liquid (water), θ – the angle of inclination, and l [m] – the water column.

Economic analysis of dryer

The economic analysis of solar dryer is an important parameter to increase acceptability for commercial applications. Payback period is the period required to get back the capital investment and the simple payback period is calculated:

$$P_{\text{b}} = \frac{C}{Pr} \tag{11}$$

where P_b is the payback period in years, C – the capital cost of solar dryer in rupees, and Pr – net profit per year.

The net profit can be calculated:

$$Pr = P_s - P_b \tag{12}$$

The cost of dried product can be calculated:

$$P = C_r + C_o + C_m + L_w + P_k \tag{14}$$

where C_r is the raw material cost of the product, C_o – the operational cost, C_m – the maintenance cost, L_w – the labor cost, and P_k – the packaging cost. Table 2 shows the economic analysis of solar dryer.

Table 2. Economic analysis of solar dryer

Capital cost of the solar dryer	C	Rs. 45,000
Loading capacity	LC	4 kg/day
Life of solar dryer	N	15 years
Raw material cost (fresh carrot) Rs. 22/kg for 1000 kg	P_r	Rs. 22,000
Electricity charge for blower Rs. 5/kWh	P_o	Rs. 3,000
Maintenance cost per year 3% of capital cost	P_m	Rs. 4,500
Labour cost (Rs. 30 per day per unit for 250 days)	L_w	Rs. 7,500
Packaging charge	P_k	Rs. 1000
Dried product selling price (Rs. 250 per kg for 216 g)	P_s	Rs. 54,000
Net profit per year	Pr	Rs. 16,000
Simple payback period	P_b	2.8 years

Rs – Rupees, official cureency in India; 1 Rs = 0.016 USD

Results and discussion

The drying characteristics of carrot slices observed in a triple pass forced convection solar dryer and the energy performance characteristics of a triple pass forced convection solar dryer are discussed in this section.

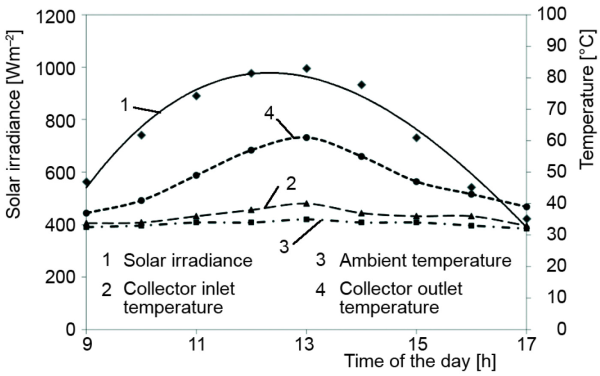

Figure 2. Variation of solar irradiance and temperatures

In fig. 2, the variation of solar irradiance, air temperature at collector inlet and outlet, and ambient temperature on a typical day observation is illustrated. The solar irradiation was varied from about 490 to 1020 W/m^2. A maximum solar irradiation of about 1020 W/m^2 was observed at 13.00 hours. The air temperature at the collector inlet was observed between 34 and 38 °C. The inlet air temperature gets increased by 1 to 6 °C due to the effect of pumping effect in the blower. It is also observed that, the outlet air temperature has minimum fluctuations due to the presence of sensible heat storage in the absorber plate and aluminum wire mesh in the path of air flow. The air collector harvests the solar energy during sunshine hours and retains the heat in the sensible heat both in heat storage medium and also in wiremesh. Moreover, the presence of wiremesh will produce turbulence effect in the path of air flow, which enhances the heat transfer coefficient between air and the absorber plate and maintains consistent temperature in the dryer cabin also.

Similarly, the hourly variation of instantaneous air collector thermal efficiency is depicted in fig. 3. The air collector efficiency was varied from about 14% to the maximum value of 63% with an average value of about 44%. High air collector thermal efficiency was observed even during off sunshine hours due to the presence of heat storage medium. The thermal efficiency of triple pass solar air collector observed in this work was found to be about 20% higher when compared to the earlier investigation reported by Banout [9]. The efficiency of triple pass dryer is 1.53% higher when compared to the double pass solar dryer using fins with an air mass flow rate of 0.06 kg/s [9]. The pick-up efficiency was varied from about 14 to about 43%. During initial stages of drying, the pick-up efficiency is in higher due to evaporation of free moisture from the surface of the product and gets reduced during latter stages of drying. The moisture ratio of carrot slices with reference to drying time is illustrated in fig. 4. From this plot, it is confirmed that, the initial moisture content of the carrot slices was reduced from about 87.5% (on wet basis) to final moisture content of about 9% in 6 hours.

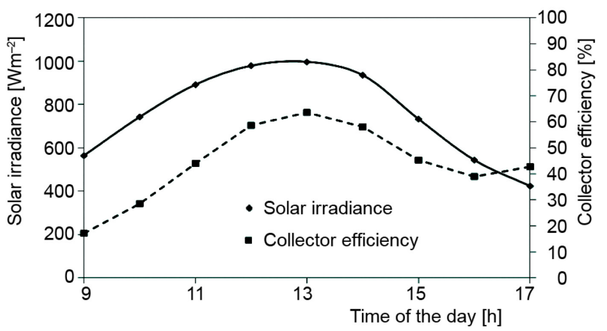

Figure 3. Hourly variation of collector thermal efficiency

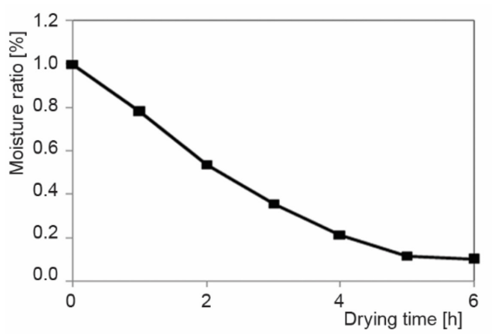

Figure 4. Variation of moisture ratio with drying time

Moreover, it is also observed that drying starts in falling rate drying period for the period of 5 hours due to the evaporation of free moisture present in the surface of the product and converted into constant drying period due to the internal moisture migration of about one hour. Temperature inside the dryer cabin was maintained higher than ambient temperature, which influences the drying duration in the case of triple pass forced convection solar dryer compared to the conventional sun drying. The pressure drop across the solar air collector with reference to different air mass flow rate is illustrated in fig. 5. From this figure, it is confirmed that the pressure drop gets increased with increase in air mass flow rate. However, the higher air mass flow rate is required to circulate through the product bed. Hence, the air mass flow rate of 0.06 kg/s was selected as an optimal value. The influence of air mass flow rate over the collector efficiency is illustrated in fig. 6. It is confirmed that maximum air collector efficiency was observed only for the air mass flow rate of 0.062 kg/s. The regression analysis was carried out for twelve thin layer drying models to correlate the drying time, t, and moisture ratio, MR, for solar drying. Based on correlation coefficient R^2, reduced chi-square χ^2 and RMSE, the Levenberg-Marquardt method was selected as curve fitting technique in non-linear regression analysis. The results of statistical analysis for modeling are given in tab. 3. Wang and Singh thin layer drying model was identified as the most suitable model for predicting the drying behavior with maximum correlation coefficient (R^2 = 0.99903) with low RMSE and reduced chi-square.

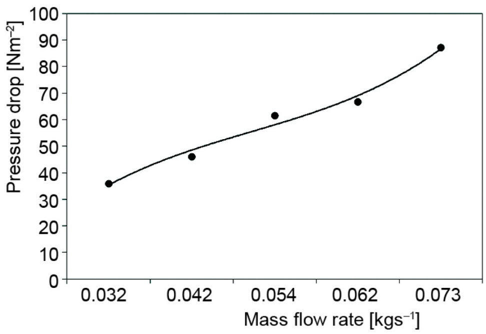

Figure 5. Pressure drop variation with air flow rate

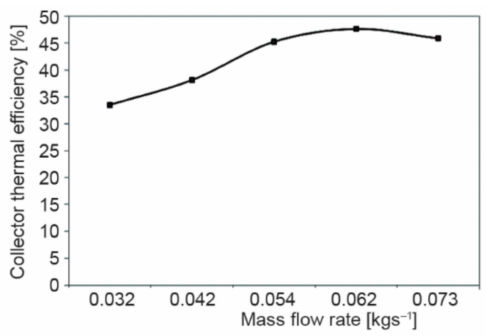

Figure 6. Variation of solar air collector thermal efficiency with the mass flow rate of air

Table 3. Statistical analysis of drying models, *MR* = *f*(*t*)

No.	Model	Model constants	R^2	χ^2	*RMSE*
1	Newton	k = 0.35293	0.98740	0.00127	0.03305
2	Page	k = 0.27783, n = 1.21422	0.99806	0.00026	0.01383
3	Modified page	k = 0.34827, n = 1.21422	0.99806	0.00027	0.01383
4	Henderson and Pabis	k = 0.36306, a = 1.02805	0.98985	0.00132	0.03075
5	Logarithmic	k = 0.27139, a = 1.16546, c = –0.15612	0.99638	0.00062	0.01884
6	Two term	k_0 = 0.36305, a = 0.58932, b = 0.43873, k_1 = 0.36308	0.98985	0.00221	0.03075
7	Two term exponential	k = 0.48831, a = 1.75334	0.99808	0.00026	0.01374
8	Diffusion approach	k = 0.616633, a = –20.09782, b = 0.96965	0.99823	0.00031	0.01322
9	Modified Henderson and Pabis	k = 0.36311, a = 0.23365, g = 0.36309, b = 0.11775, c = 0.67666, h = 0.36304	0.98985	0.00662	0.03075
10	Verma *et al.*	k = 0.16338, a = –8.51272, g = 0.17812	0.99658	0.00058	0.01816
11	**Wang and Singh**	$\boldsymbol{a}$ **= –0.27909,** $\boldsymbol{b}$ **= 0.02124**	**0.99903**	**0.00013**	**0.00973**
12	Midilli and Kucuk	k = 0.27468, a = 0.99617, b = –0.00017, n = 1.21879	0.99807	0.00044	0.01375

Conclusions

The drying characteristics of carrot in a triple pass forced convection solar dryer was investigated and following conclusions are drawn.

- The initial moisture content was reduced from about 87.5% (wet basis) to final moisture content of 10% on wet basis in 6 hours.
- The quality of the dried product was found to be good when compared to other drying modes.
- The air mass flow rate was optimized to 0.062 kg/s.
- The dryer pick-up efficiency was varied between 14 and 43%.
- The average dryer thermal efficiency was calculated to be about 44%.
- The drying model proposed by Wang and Singh was found to be good drying model for predicting the drying characteristics of carrot in a triple pass forced convection solar dryer.

The results reported in this paper confirmed that, triple pass solar dryer is more suitable for processing carrot slices with good energy efficiency.

Nomenclature

A_c – area of the solar air heater, [m^2]
C – captial cost, [Rs]
c_p – specific heat, [$kJkg^{-1}K^{-1}$]
E_{abs} – energy absorbed by the dryer, [kW]
H_i – the absolute humidity of air entering the chamber, [kg per water per kg of dry air]
H_s – the adiabatic saturation humidity of air entering the chamber, [kg per water per kg of dry air]
h_{fg} – latent heat of evaporation, [$kJkg^{-1}K^{-1}$]
I – solar irradiation, [Wm^{-2}]
k – drying constant
LC – loading capacity, [kg]
M – moisture content on wet basis, [%]
M_e – equilibrium moisture content, [%]
M_i – initial moisture content, [%]
MR – moisture ratio, [–]
M_t – moisture content on wet basis at time t, [%]
$\dot{m}_a$ – mass flow rate of air, [kgs^{-1}]
m_{evap} – moisture evaporated, [kg]
m_f – final mass of the product, [g]
m_i – initial mass of the product, [g]
N – life of the dryer, [years]
T – temperature, [°C]
t – time, [s]
W_o – sample weight at $t = 0$, [kg]
W_t – sample weight at any time t, [kg]

Greek symbols

η_p – pick-up efficiency, [%]
η_{the} – dryer thermal efficiency, [%]

References

[1] Prakash, S., *et al.*, Performance Evaluation of Blanched Carrots Dried by Three Different Driers, *Journal of Food Engineering, 62* (2004), 3, pp. 305-313
[2] Sharma, A., *et al.*, Solar-Energy Drying Systems: A Review, *Renewable and Sustainable Energy Reviews, 13* (2009), 6-7, pp. 1185-1210
[3] Aboul-Enein, S., *et al.*, Parametric Study of a Solar Air Heater with and without Thermal Storage for Solar Drying Applications, *Renew. Energy, 21* (2000), 3, pp. 505-522
[4] Jain, D., Modeling the System Performance of Multi-Tray Crop Drying Using an Inclined Multi-Pass Solar Air Heater with In-Built Thermal Storage, *Journal of Food Engineering, 71* (2005), 1, pp. 44-547
[5] El-Sebaii, *et al.,* Year Round Performance of Double Pass Solar Air Heater with Packed Bed, *Energy Conversion and Management, 48* (2007), 3, pp. 990-1003
[6] Mohanraj, M., and Chandrasekar, P., Drying of Copra in a Forced Convection Solar Drier, *Biosystems Engineering, 99* (2008), 4, pp. 604-607
[7] Aldabbagh, L. B. Y., *et al.,* Single and Double Pass Solar Air Heaters with Wire Mesh as Packing Bed, *Energy, 35* (2010), 9, pp. 3783-3787
[8] Omojaro, A. P., *et al.*, Experimental Performance of Single and Double Pass Solar Air Heater with Fins and Steel Wire Mesh as Absorber, *Applied Energy, 87* (2010), 12, pp. 3759-3765

[9] Banout, J., Design and Performance Evaluation of a Double-Pass Solar Drier for Drying of Red Chilli (Capsicum annum L.), *Solar Energy, 85* (2011), 3, pp. 506-515
[10] Fudholi, A., *et al.*, Performance and Cost Benefits Analysis of Double-Pass Solar Collector with and without Fins, *Energy Conversion and Management, 76* (2013), Dec., pp. 8-19
[11] Akpinar, K. E., Bicer, Y., Mathematical Modelling of Thin Layer Drying Process of Long Green Pepper in Solar Dryer and Under Open Sun, *Energy Conversion and Management, 49* (2008), 6, pp. 1367-1375
[12] Vijayan, S., *et al.*, Mathematical Modeling and Performance Analysis of Thin Layer Drying of Bitter Gourd in Sensible Storage Based Indirect Solar Dryer, *Innovative Food Science and Emerging Technologies, 36* (2016), 1, pp. 59-67
[13] Vishwanathan, K. H., *et al.*, Infrared Assisted Dry-Blanching and Hybrid Drying Of Carrot, *Food and Bioproducts Processing, 91* (2013), 2, pp. 89-94
[14] Montero, I., *et al.,* Design, Construction and Performance Testing of a Solar Dryer for Agroindustrial By-Products, *Energy Conversion and Management, 51* (2010), 7, pp. 1510-1521
[15] Shanmugam, V., Natarajan, E., Experimental Investigation of Forced Convection and Desiccant Integrated Solar Dryer, *Renewable Energy, 31* (2006), 8, pp. 1239-1251

Paper submitted: April 4, 2017
Paper revised: May 25, 2017
Paper accepted: June 23, 2017