

Numerical and economic analysis of solar thermal collectors for indirect solar dryer applications

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Abstract

*Solar air heaters is a type of heat exchanger that intercepts solar radiation, converts into heat and transfers to the air medium. Solar air heaters plays a major role in many engineering low temperature thermal applications thereby reducing the extensive usage of conventional fossil fuels. The applications of solar air heaters includes space heating, process heat, drying, night cooling and ventilation applications. The prime aim of this study is to analyze the theoretical and thermal performance of indirect solar dryer. The theoretical efficiency of the solar dryer is 54%. A solar dryer has been designed and tested its performance for drying *Daucuscarota subsp. Sativus*(carrot). The drier is loaded fresh carrot slices. The primary moisture content of 89% is reduced to preferred moisture level of 11% in 6h using solar dryer. Whereas hot air oven and open sun drying took 7h and 8h to dehydrate the moisture of carrot to the desired level. In addition economic analysis of solar drier has also been carried out to estimate the annual savings, life cycle savings and payback duration of the system. The economic analysis shows that, the capital cost invested to develop solar drier is retrieved in 0.75 years.*

1. Introduction

Solar energy is the most abundant form of renewable energy that has enormous potential, not only in electricity generation but also for many industrial thermal applications. Solar energy improves our energy security by reducing the usage of expensive fossil fuels for applications like water heating, space heating, thermal electricity generation and industrial process heating systems. Among many industrial thermal applications, drying food materials is an energy substantial process which consume almost 10-15% of nation's industrial energy consumption.

Drying agricultural food products is considered to be the most important food preservation technique to reduce post-harvest losses. Drying is the method of expulsion of water to the minimum desired level from the food products to enhance the shelf life, minimize storage losses, reduce storage space and transportation cost [1]. Many solar driers in practice use flat plate solar collectors. This type of solar collectors has disadvantages such as low heat transfer coefficient, low thermal capacity and less thermal efficiency. Therefore it is necessary to design of solar collectors to have high heat transfer characteristics between absorber and air. Modification in absorber with different geometries like V-grove, finned, corrugated and matrix would help to

achieve high thermal efficiency. However before practical implementation, optimization and prediction of thermal performance of solar dryers cannot be known until it is numerically simulated. Several authors studied various design aspects of solar dryers through numerical simulations which was then verified through practical experiments [2]. Apart from heat transfer characteristics and thermal performance studies it also imperative to evaluate about technical and economic aspects of solar dryers.

The primary aim of this research work is to design, develop and study the thermal performance of indirect solar dryer with flat plate collectors. A flowchart in Fig.1 gives the outline of the work presented in this paper. In this present paper the efficiency of the solar dryer is studied through numerical analysis. *Daucuscarota subsp. Sativus* (Carrot) is used to evaluate the efficiency and economical studies of solar dryer. A comparative study on removal of moisture from carrot was carried out to compare the drying kinetics with open sun drying, oven drying and solar drying. Economic analysis of the solar dryer is studied to have knowledge on annual savings and payback period.

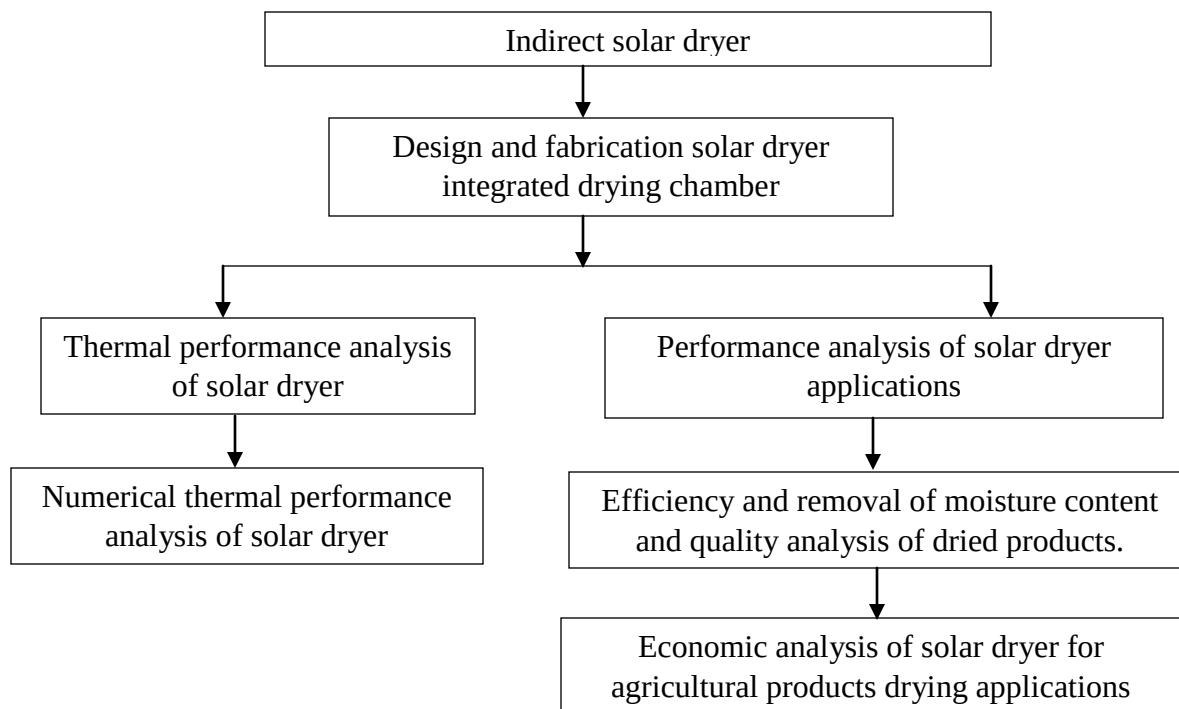


Fig.1 Outline of the research work carried out presented in this paper.

2. Materials and Method

2.1 Modelling solar air heater

Solar matrix air heaters are highly suitable for high temperature applications than flat plate, vee corrugated and finned type air heaters. The matrix air heaters achieves higher efficiencies than other solar air heaters due to increased contact area between the air medium and wire mesh. Matrix air heaters are usually made of porous wire mesh [3]. The efficiency depends on the mesh size and porosity of the wire mesh. The heat exchanger mechanism depends on the packing of matrix wire mesh.

The geometrical modelling is performed using radiative, top and bottom loss and convective heat transfer coefficients and various temperatures like absorber, glass, air inlet and outlet [4]. A flowchart describing the logic of the modelling is given in fig.2. A schematic diagram of solar dryer with different geometrical modelling parameters is shown in fig. 3.

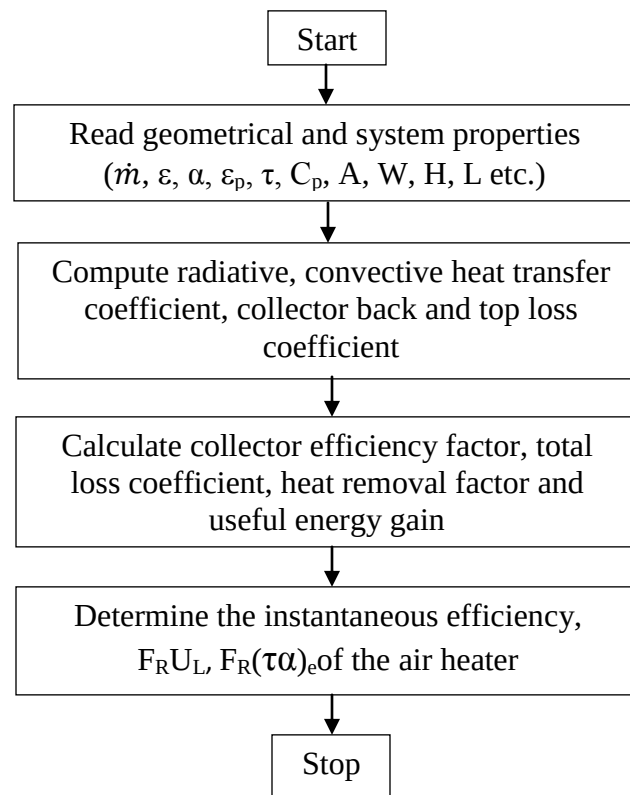


Fig. 2 Flowchart showing the logic behind the numerical modelling.

Numerical simulation on thermal performance is executed by assuming the following steady state conditions,

- i. Thermo-physical properties of absorber and air is stable over the collector area and do not vary with temperature.
- ii. Radiation and convection losses occurs from air heater top and bottom surface.

iii. Heat transfer and air flow are one dimensional.

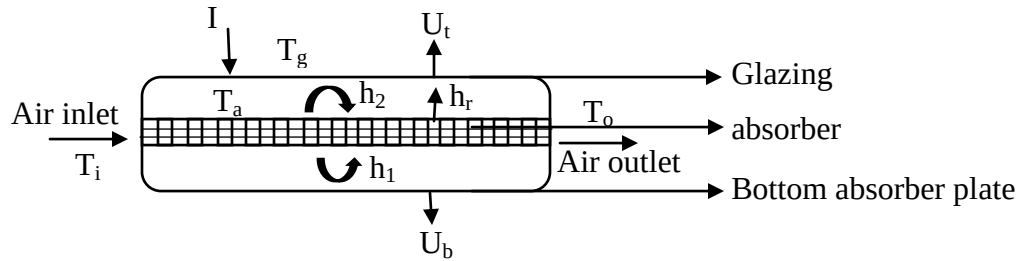


Fig. 3 Solar dryer with numerical modelling parameters.

The energy balance equation for absorber and fluid is represented by following equations for air flowing parallel to the absorber.

$$s = h_v D(t_b - t_f) + U_L(t_b - t_a)$$

$$h_v A(t_b - t_f) = \dot{m} C_p \frac{dt_f}{dx}$$

The collector efficiency (F') and collector total loss coefficient (U_L) is given by the following expressions,

$$F' = \frac{H + h_2 U_t}{(U_t + h_r + h_1)(U_b + h_r + h_2) - h_r^2}$$

$$U_L = \frac{H(U_b + U_t) + U_b U_t (h_1 + h_2)}{H + h_2 U_t}$$

$$H = h_1 h_r + h_2 h_r + h_1 h_2$$

$$h_r = \frac{\sigma(T_1^2 + T_2^2)(T_1 + T_2)}{\frac{1}{\epsilon_c} + \frac{1}{\epsilon_p} - 1}$$

The top loss and back loss coefficient is given by

$$U_t = h_w + h_{r,g-ciel}$$

$$h_w = 2.8 + 3 v_{vent}$$

$$h_{r,g-ciel} = \epsilon_c \sigma (T_g^2 + T_{ciel}^2) (T_g + T_{ciel})$$

$$T_{ciel} = 0.0552 T_a^{1.5}$$

$$U_b = \frac{1}{\left[\frac{1}{h_{r,p-b} + h_{c,p-b}} + \frac{e_{is}}{\lambda_{is}} + \frac{e_{caisson}}{\lambda_{caisson}} + \frac{1}{h_w} \right]}$$

The radiative and convective heat transfer coefficient are determined by the expression given below,

$$h_{r,p-b} = h_{r,p-g}$$

$$h_{c,p-b} = 0.61 \left[\frac{(T_p - T_a)}{L^2} \right]^{1/5} + 1.42 \left[\frac{(T_p - T_a)}{L} \right]^{1/4}$$

According to Hottel-Whillier-Bliss the collector heat removal factor (F_R) and efficiency (η) is defined by,

$$F_R = \frac{\dot{m}C_p}{A_c U_L} \left[1 - \exp \left(- \frac{A_c U_L F'}{\dot{m}C_p} \right) \right]$$

$$\eta = \frac{q_u}{I} = F_R \left[(\tau\alpha) - U_L \frac{(T_p - T_a)}{I} \right]$$

2.2 Drying analysis

The drying features of the solar dryer is a function of solar radiation, inlet air temperature, dryer design, drying kinetics and size, shape and product. The thermal efficiency of the dryer is estimated using Eq. (1)

$$\eta_d = \frac{ML}{I_c At} \quad (1)$$

The quantity of moisture present in drying product is determined on wet basis. The initial and final mass of the product is measured using weighing balance [5,6]. The moisture content was calculated by using Eq. (2).

$$M\% = \frac{M_i - M_f}{M_i} \times 100 \quad (2)$$

The mass loss is estimated at regular interval expressed using Eq. (3).

$$M_l = (M_i - M_f) \quad (3)$$

Specific Moisture Extraction Rate (SMER) is used to determine the dryer's effectiveness. It is estimated by the by the equation. (4).

$$SMER = \frac{\text{Moisture removed from product}}{\text{Energy input}} \quad (4)$$

Similarly the Moisture Extraction Rate (MER) is defined as the quantity of moisture removed per unit time from a product and is given by Eq. (5).

$$MER = \frac{\text{Moisture removed from product}}{\text{Drying time}} \quad (5)$$

Saving in drying period using solar dryer with respect to open sun drying and oven drying is calculated using Eq. (6) and is expressed in percentage.

$$S_T \% = \frac{t_o - t_s}{t_o} \times 100 \quad (6)$$

2.3 Economic analysis

Solar drying is not only an energy conserving process but also a process of making products of good quality. The quality of the product has an effect on the economy of various drying techniques. When the quality of the product is better, results in high selling price. Increase of marketing income achieved by better quality leads to higher savings per year which in turn reduces the payback period.

Economic analysis of indirect solar dryer have been studied in comparison to the conventional dryer, that depends on various parameters like capital cost, rate of interest, conventional energy prices, quality and prices of dried products [7]. Economic evaluation of solar dryer were calculated using, annualized cost, life cycle savings and payback period.

Annualized cost is defined as the total expenses incurred to operate, maintain and owning the indirect solar dryer per year. The annualized cost of the dryer (C_a) is calculated as per following equation

$$C_a = C_{ac} + C_m - V_a + C_{rf} + C_{re}$$

where C_{ac} annualized capital cost, C_m annualized maintenance cost (15% of annualized capital cost), V_a annualized salvage value, C_{rf} annual running fuel cost and C_{re} annual electricity cost for solar dryer.

The price of drying per unit weight of the dried product can also be calculated using annualized cost estimation [8]. The price of drying (C_s) per kilogram is calculated by the annualized cost of the dryer to the quantity of product dried per annum as given in equation.

$$C_s = \frac{C_a}{M_y}$$

$$M_y = \frac{M_d D}{D_b}$$

Where C_a is annualized cost of dryer, M_y mass of product dried per year, M_d mass of dried product per batch, D number of drying days and D_b number of drying days per batch.

Life cycle savings technique is used to calculate the total savings incurred from the entire lifetime of the solar dryer. Estimation of savings per kilogram, savings per batch and savings per day gives the annual savings of solar dryer given by the equation [9]. The present worth is obtained by the equation given below. The life cycle savings of the dryer is calculated by the sum of present worth over the life span of the dryer.

$$S_j = S_d * D * (1 + i)^{j-1}$$

$$P_j = F_{pj} * S_j$$

$$F_{pj} = \frac{1}{(1 + d)^j}$$

Payback period method is used to evaluate the amount of time taken for a system to recover its initial cost. A system with short payback period promises the quick inflow of initial annualized cost and reduce the loss due to variable economic conditions. Payback period is calculated using equation

$$N = \frac{\ln\left(\frac{C_{cc}}{S_1}(d - i)\right)}{\ln\left(\frac{1+i}{1+d}\right)}$$

3. Results and Discussion

3.1 Dryer analysis.

The recital of the indirect solar dryer interms of removal of moisture content, drying time required, time saved in drying, moisture extraction rate, specific moisture extraction rate and efficiency is studied with respect to electrical and open sun drying. The change in moisture content (wet basis) with drying time of *Daucuscarota subsp. Sativus* (carrot) with different drying techniques is illustrated in Fig.4. The primary moisture content of carrot was 88.7% reduced to the desired moisture level of 11.3%. Total drying time required by solar dryer to reach desired moisture level is 6 hours and 30 minutes whereas it took 8 hours and 7 hours for open sun and electrical drying. Thermal efficiency of indirect forced convection solar drier is found to be 52%. It is found that by using solar dryer 44% and 37.5% of time is saved with respect to open sun and hot air oven drying.

Specific moisture extraction rate (SMER) is used to measure the quantity of moisture removed from the product for the given amount of energy. The SMER for solar drier and hot air oven drier was estimated to be 12 kg/kWh and 2.5 kg/kWh. It can be seen that the solar drier has highest specific moisture extraction rate per kilowatt hour of energy supplied. Amount of moisture extracted per hour is determined using moisture extraction rate (MER). Table 1 shows comparison of drying performance analysis of indirect forced convection dryer with hot air oven and open sun drying. The moisture removal rate is found to be 3.37 kg/hr, 3.85 kg/hr and 4.50 kg/hr for open sun, hot air oven and solar drying. The results obtained through MER analysis shows that solar drying removes maximum moisture within short span of time than hot air oven and open sun drying.

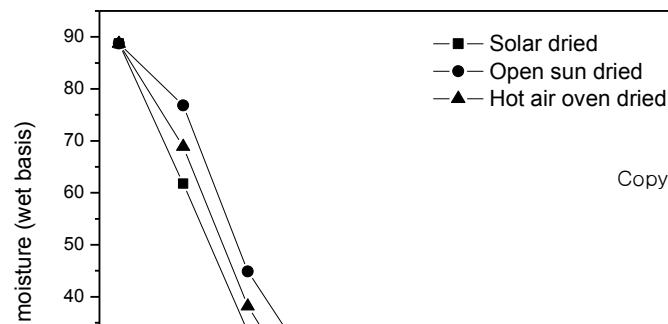


Fig. 4 Removal of moisture content with respect to different drying techniques.

Table 1 Comparison of drying characteristics of different drying techniques.

S.No	Drying method	Total drying time (Hours)	Drying time saved using solar drying (%)	Moisture extraction rate (MER) (kg/hr)	Specific moisture extraction rate (SMER) (kg/kWh)
1	Open sun	8	44	3.37	-
2	Hot air oven	7	37.5	3.85	2.5
3	Solar drying	6.30	-	4.50	12

3.2 Economic analysis

The economic analysis of the developed solar dryer is studied to commercialize the system for agricultural food crops drying applications. Economic analysis of developed solar dryer to dry *Daucuscarota subsp. Sativus* (carrot) is calculated and compared with electrical dryer. The annualized cost was estimated using capital cost, maintenance cost, salvage value and running fuel cost. The initial cost of the solar and electrical dryer is Rs. 1,30,000. The annual maintenance cost of solar and electrical dryer is assumed to be 10% of capital cost. The solar dryer system is equipped with 0.5hp blower and presumed to operate 220days per year. The electricity cost per unit incurred to run the blower is also taken into account to calculate annual cost of the dryer. The annual capital cost of solar dryer and electrical dryer is calculated to be Rs. 33,447 and Rs. 52,561. It is estimated that the price of drying per kilogram of carrot is Rs.51 and Rs.80 for solar and electrical dryer.

Table 2 Life cycle savings of solar dryer for agricultural food crop (carrot) drying applications

Year	Annual savings	Present worth	Cumulative present worth
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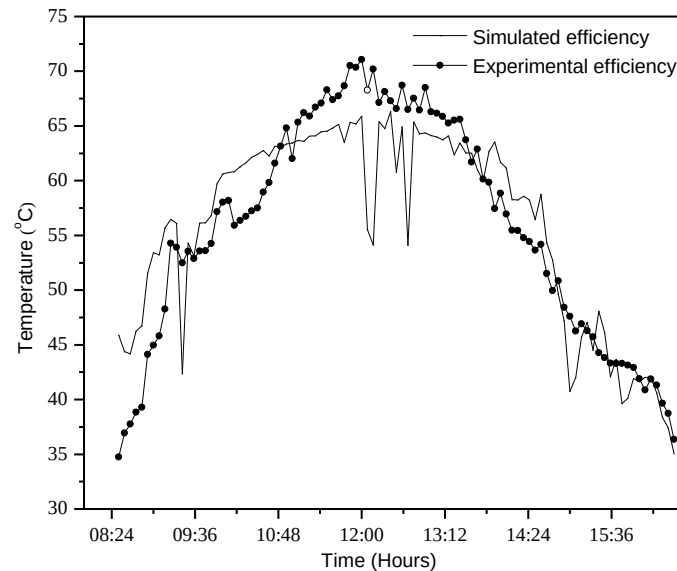
1	1.86	1.73	1.73
2	1.97	1.69	3.42
3	2.08	1.66	5.08
4	2.21	1.63	6.71
5	2.36	1.63	8.34
6	2.51	1.60	9.94
7	2.66	1.59	11.53
8	2.82	1.58	13.11
9	3.01	1.56	14.67
10	3.20	1.53	16.20

Life cycle savings of solar dryer is assessed using annual savings and present worth. The annual savings is evaluated by calculating the savings per day considering a loading capacity of dryer per batch, number of working days and number of batches per year. The developed solar dryer has a loading capacity of 30kg of carrot per batch. It can be noted that it requires only one day to dry one batch of carrot. The savings earned by drying 30kg of carrot is found to be Rs.846 per day. Annual savings, present worth and cumulative present worth of solar dryer for drying carrot is shown in Table 2. The cumulative present worth of annual saving is approximately Rs.16.20 lakhs. Thus by using life cycle savings method it is concluded that by investing Rs.1.30 lakhs on this particular solar dryer system will yield Rs.16.20 lakhs at the end of 10 years.

Payback time is evaluated to analyze the time required to retrieve the initial investment spent in developing solar dryer. Payback time is calculated and is found to be 0.69 year which is approximately 252 days which is very much less compared to the life span of the solar drying system.

3.3 Numerical analysis

The numerical studies on efficiency of solar drier is evaluated in matlab with respect to the received solar radiation. The efficiency of solar dryer is shown in Fig. 5. The numerical results



shows that the efficiency of solar dryer is 43% which correlates with experimental results. The maximum efficiency of solar dryer is 66% which is achieved around 13:00 hours. It is observed that the efficiency of solar dryer is influenced by the solar radiation.

Fig. 5 Numerical efficiency of solar dryer.

Conclusion

Solar dryers offers several advantages such as increased drying rate, significant reduction in drying time, reduced losses with improved food quality and greater income. However, different designs have different efficiencies therefore it becomes necessary to numerical studies on various design parameters before design and fabrication. The present work is composed of numerical, economic and dryer analysis of indirect solar dryer. The results shows that the designed indirect solar dryer has an average efficiency of 43% with superior drying characteristics. The payback time of solar dryer is less than a year and therefore the proposed solar dryer has great income when used for agricultural applications.

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