

Performance of Solar Drying Systems : A Case Study of Nepal

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Research and Development works on different types of solar dryers have been taking place since 1970s in the country. Out of several solar drying systems that are presently available in various parts of the world three types ie, cabinet, rack and tunnel, are being commonly used in Nepal. Their operations are based on either direct or indirect or mixed mode of heating. In the past, only a very limited number of studies have been made in determining the performances of solar dryers manufactured and installed so far in the country. As a result, very few information is available on their field performance. The present study is an attempt towards determining the thermal efficiencies of different types of solar dryers installed at different parts of the country. In this paper a straight forward steady state analysis has been adopted to evaluate the performance of solar dryers by using simple basic energy balance equations. All mathematical expressions related to energy interactions are expressed in simple and separate forms. Data obtained from twenty laboratories as well as outdoor field tests have been used in the calculation of thermal efficiencies. Tests were carried out on 12 different solar dryers including 3 solar cabinet dryers, 6 solar rack dryers, 2 solar tunnel dryers and 1 hybrid solar/biomass rack dryer. The maximum value of thermal efficiency obtained from these tests is found as 22.1% for solar cabinet dryer, 21.4% for solar rack dryer and 21.7% for solar tunnel dryer.

Keywords: 'Solar radiation'; Solar collector; Heat energy; Moisture content; Air circulation; Drying rate; Drying time.

NOTATION

A	: area, m^2
C	: specific heat capacity, $J/kg\text{-}^\circ K$
C_p	: specific heat capacity at constant pressure, $J/kg\text{-}^\circ K$
F	: configuration factor, a function of two surfaces
F'	: collector efficiency factor
F''	: collector flowing factor
Fr	: collector heat removal factor
G	: mass flow rate, m^3/s
h	: heat transfer coefficient, $W/m^2\text{-}^\circ K$
h_{fg}	: heat desorption of water, J/kg
h_v	: volumetric heat transfer coefficient, $J/m^3\text{-}^\circ K\text{-}s$
H	: specific humidity of air, kg/kg
I	: intensity of solar radiation, W/m^2
k	: drying rate constant, sec^{-1}
K	: thermal conductivity of the food, $W/m\text{-}^\circ K$
M	: moisture content (db), ratio
M_e	: equilibrium moisture content (db), ratio

q	: rate of convective heat transfer, J/s
t	: time, s
T	: temperature, $^\circ K$
T_{fm}	: average of air temperature, $^\circ K$
T_{pm}	: average of plate temperature of absorbers, $^\circ K$
U_1	: overall heat loss coefficient
W	: weight, kg
x	: distance, m
α	: absorptance
ΔT	: change in temperature $^\circ K$
$\Delta T_{T-F} \Delta X^1$: rate of temperature change along length of heat flow path x , $^\circ K/m$
ϵ	: emissivity
η	: efficiency
λ	: latent heat of vaporization, J/kg
ρ_g	: bulk density of dry product, kg/m^3
σ	: Stefan–Boltzmann's constant, 5.67×10^{-8} , $W/m^2\text{-}^\circ K^4$
τ	: transmissivity

SUBSCRIPTS

a	: ambient / air
f	: food receiving radiant heat
F	: Food, total solid content in food
g	: product
H	: water

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- i : inlet
 t_2-t_1 : time interval
 T : tray radiating heat
 v : water vapor
 y : dryer radiating heat

INTRODUCTION

The developmental activities on solar dryers have been taking place in Nepal for over two decades. Their operations are based on either direct drying (solar cabinet dryer) or indirect drying (some versions of solar rack dryers) or mixed drying (solar tunnel dryers and some other versions of solar rack dryers). With the exception of solar tunnel dryers and large size solar rack dryers, which are based on forced circulation of airflow, most of the dryers developed so far run on natural circulation of airflow¹. Recently, a new concept of hybrid drying technology has also emerged.

At present, a number of government, non-government and private organizations along with a few research institutions are involved in the fabrication, promotion and dissemination of solar dryers in Nepal. But, the solar dryers used by them have undergone hardly any systematic tests to assess their field performance. Drying efficiencies of most of the solar dryers that are manufactured and installed so far are not yet fully assessed. This study is being initiation towards properly analyzing the field performance of these solar drying systems.

The analytical part of this study provides an overview on how efficiently the food in a given mode of solar drying system uses the heat to warm up and evaporate the water. The analysis is based on either drying rates of foods or its thermal performance. It uses a state forward steady state analysis for drying by using simple basic heat transfer equations. All the energy interactions are expressed separately and the mathematical expressions are arranged in a simple way. Some laboratories as well as field tests have been performed and data obtained therefrom are used in simple basic one-dimensional energy balance equation to calculate the thermal efficiency.

PRINCIPLE OF SOLAR DRYING

The purpose of drying is to reduce the moisture content of the product to a safe level to minimize the deterioration of the quality of product during storage. Drying rate of the product is controlled by the rate at which the product's internal moisture is released from its surface and the rate at which moist air is removed from the area surrounding the product. The changes in temperature and moisture content of the products with time and position during dehydration process can be described by the following four equations². The rate of change of moisture content in the product is given by

$$\frac{\partial M}{\partial t} = -k(M - M_e) \quad (1)$$

The exchange of moisture between the product and air is given by

$$G_a \frac{\partial H}{\partial t} = -\rho_g \frac{\partial M}{\partial t} \quad (2)$$

The exchange of energy between air and product can be written as

$$Ga(C_a + C_v H) \frac{\partial T}{\partial x} = \rho_g C_v (T_a - T_g) \frac{\partial M}{\partial t} - \rho_g (C_g + C_H M) \frac{\partial T}{\partial t} + \rho_g h_{fg} \frac{\partial M}{\partial t} \quad (3)$$

The rate of heat transfer between air and product is described by

$$\rho_g (C_g + C_H M) \frac{\partial M}{\partial T} = h_v (T_a - T_g) + \rho_g h_{fg} \frac{\partial M}{\partial T} \quad (4)$$

EFFICIENCY OF SOLAR DRYERS

The efficiency of solar drying systems can be evaluated either based on the thermal performance or drying rates of the products. The process based on drying rates is associated with a number of variables involved and is much complex and tedious for calculation³. This study is an attempt to evaluate the thermal performance of different solar dryers.

The thermal efficiency of solar dryer can be defined as the thermal energy utilized for drying over the thermal energy available for drying.

The term 'thermal energy utilized for drying' includes the following parameters :

- (a) Sensible heat used to raise the temperature of the food, given by

$$W_F C_{PF} (\Delta T)_{t_2-t_1}$$

- (b) Sensible heat used to raise the temperature of the water in the food, given by

$$W_H C_{PH} (\Delta T)_{t_2-t_1}$$

- (c) Latent heat used to vaporize the water in the food, given by

$$W_v (\lambda_v)$$

Thus, the thermal efficiency of solar drying system is given by the relation³.

$$\text{Efficiency SD} = \frac{\text{Heat}_{\text{Sensible(H\&F)}} + W_v \lambda_v}{q_{\text{input}}}$$

Radiant energy from the sun can be used in two ways: either heating up ambient air in a solar air heater and drying the products with heated air or heating up the products directly through absorption of solar radiation by the wet product. The second method is more economic and easier, since no heat transfer losses occur. But, while drying the vegetables containing higher amount of vitamin A and other several medicinal and herbal products these must not be exposed to direct sunlight. Both the types (direct and indirect mode of heating as well as combination of both) of these devices are discussed here separately.

Direct Solar Radiant Drying (DSRD)

This is the simplest case and the oldest practice of drying by using a flat surface (ground or mat) for direct solar drying. In this case, the available energy is primarily the radiant heat from the sun neglecting the heat from the drying surface. There is some additional convective heat from the air (heated by the sun) above and around the food being dried. The amount of convective heat from the air above and around the food is

$$q - hA\Delta T_{\text{Air-Food}} \quad (5)$$

Since both radiant heat available from the sun and the convective heat from the air passing through the drying product vary with time and the climate during a given day, h and $\Delta T_{\text{Air-Food}}$ will be changing. An hourly solar drying efficiency will be

$$\text{Efficiency}_{\text{DSRD}} = \frac{(W_F C_{PF} + W_H C_{PH})\Delta T_{t_2-t_1} + W_v \lambda_v}{q_{\text{Insolation}} + hA\Delta T_{\text{Air-Food}}} \quad (6)$$

Direct Solar Drying (DSD)

In the case of direct solar dryer, following several sources of thermal energy are available for drying:

- (i) Solar radiation, $q_{\text{insolation}}$
- (ii) Convective heat from air inside the dryer to the food, $q_{\text{heated air}}$
- (iii) Radiant heat from the dryer body to the food, $q_{\text{dryer radiation}}$
- (iv) Radiant heat from the drying trays to the food, $q_{\text{tray radiation}}$
- (v) Conductive heat from drying trays to the food, $q_{\text{tray conduction}}$

The first two 'q' terms are about the same as in case of DSRD with some variations. In case of DSRD, the solar radiant heat is for a single layer of food, which is completely exposed to the sun. In case of DSD, the drying trays be more than one. Depending upon the relative position of the dryer to the sun, most of the trays except the top one are only partially exposed to the sun. Therefore, the amount of direct solar radiation to each tray varies and will require separate, precise measurements. For case of calculation, in this study, direct pyranometer reading per unit glazing area is taken instead of separate measurements.

The amount of convective heat from the air inside the dryer is similar to that in case of DSRD but the air movement in case of DSD is somewhat restricted due to all four sides and the top of the dryer plus the number of trays. Both 'h' and 'ΔT' in case of DSD are probably smaller than those in case of DSRD.

The two 'q' terms represent the heat that the dryer body and the trays radiate to the food after having absorbed some radiant heat from the sun. These are difficult to measure and complicated to calculate because the temperatures of many parts of the dryer body and the trays vary with time. The emissivity and configuration factors also have to be estimated. Basically, Stefan-Boltzmann's law

for thermal radiation could be used for a rough estimate and is calculated as

$$q_{R_d} = \sigma \epsilon A_F (T_y^4 - T_F^4) \quad (7)$$

and

$$q_{R_a} = \sigma \epsilon A_F (T_T^4 - T_F^4)$$

The fifth 'q' term is the conducting heat from drying trays to the food after being heated up gradually by the sun and the air. Compared with other 'q' terms, this one might probably be small. To calculate this term, Fourier law could be used

$$q_{\text{cond}} = K A \Delta T_{\text{Tray-Food}} \Delta x^{-1} \quad (8)$$

For a direct solar dryer, an hourly solar drying efficiency will be:

Efficiency DSD =

$$\frac{[(W_F C_{PF} + W_H C_{PH})\Delta T_{t_2-t_1} + W_v \lambda_v]}{[q_{\text{Insolation}} + hA\Delta T_{\text{Air-Food}} + \sigma \epsilon A_F (T_y^4 - T_F^4) + \sigma \epsilon A_F (T_T^4 - T_F^4) + kA\Delta T_{\text{Tray-Food}} \Delta x^{-1}]} \quad (9)$$

Indirect Solar Dryer (ISD)

Sources of thermal energy available for drying in the indirect mode are:

- (i) convective heat from the air being heated in the solar collector, $q_{\text{heated air}}$
- (ii) radiant heat from the dryer body, $q_{\text{dryer radiation}}$
- (iii) radiant heat from drying trays, $q_{\text{tray radiation}}$
- (iv) conductive heat from drying tray, $q_{\text{tray conduction}}$

The primary source of thermal energy for drying in this mode is the first 'q' term. The heat is supplied not only to the food but also to the trays and inside of the dryer body. The heat transfer coefficient in this case should be higher than that in case of DSRD and DSD. Here, this 'q' amount of energy is available due to solar air heater. Therefore, the losses in the solar collector must be considered while calculating the overall thermal efficiency of the dryer.

Radiant heat from the dryer body could contribute a certain amount of heat for drying if the side panels and the dryer top are made of metal provided with black coating.

The amounts of radiant and conductive heat from the trays are not as large as the first two 'q' terms. However, since the trays are heated up continuously by the hot air from the solar collector, the amounts of heat are not necessarily negligible.

For an indirect solar dryer, an hourly solar d will be:

Efficiency ISD = η_C

$$\frac{[(W_F C_{PF} + W_H C_{PH})\Delta T_{t_2-t_1} + W_v \lambda_v]}{[hA\Delta T_{\text{Air-Food}} + \sigma \epsilon A_F (T_Y^4 - T_F^4) + \sigma \epsilon A_F (T_T^4 - T_F^4) + kA\Delta T_{\text{Tray-Food}} \Delta x^{-1}]} \quad (10)$$

Where, η_c is thermal efficiency of solar collector and is generally expressed in the following three forms⁴.

$$\eta_c = Fr[(\tau\alpha) - U_1(\frac{T_i - T_a}{I})],$$

$$\eta_c = F''[(\tau\alpha) - U_1(\frac{T_{pm} - T_a}{I})],$$

$$\eta_c = F'[(\tau\alpha) - U_1(\frac{T_{fm} - T_a}{I})] \quad (11)$$

Combined Mode Solar Dryer

In this case the sources of thermal energy available for drying are the combination of all the 'q' terms in case of DSD and ISD. The

two largest thermal energy sources are the solar radiant heat ($q_{insolation}$) in case of DSD and the convective heat from the air being heated in the solar collector ($q_{heated\ air}$) in case of ISD. The remaining 'q' terms also contribute heat to drying, and the amounts are comparable to or larger than those in the direct and indirect mode.

FIELD TEST PROCEDURE FOR SOLAR DRYERS

It is not possible to test all types of dryers for all typical climates and crops. It is also difficult to adapt higher order mathematical equations in the field tests to evaluate the performance of these systems. Hence a standard method for testing of the dryers is developed which includes simulation of air heating, solar radiation and relative humidity conditions. The net energy requirement obviously depends on the efficiency of the dryer and it is defined as²

Table 1 Details of data obtained from field tests of different solar dryers

Site of Installation	Type of Dryer	Collector Size, m ²	Drying Capacity kg, Fresh	Airflow, Type	Date of Experiment	Material	Av Solar Radiation W/m ²	Time Taken, h	Thermal Efficiency %
IOE, Pulchowk, Lalitpur	SRD	1.65	4	Natural	Aug 28-30, 2002	Cauliflower	564	11	20.5
IOE, Pulechowk, Lalitpur	SRD	1.65	4	Natural	Aug 31 and Sept 01, 2002	Cauliflower	620	10	20.4
IOE, Pulchowk, Lalitpur	SRD	1.65	4	Natural	Sept 02-03, 2002	Cauliflower	649	9	21.4
Kalyanpur VDC, Chitwan	SRD	12.5	40	Forced (15W)	Dec 01-02, 2000	Cocoon	580	12	16.1
Kalyanpur VDC, Chitwan	SRD	12.5	40	Forced (15W)	Apr 21-22, 2001	Cocoon	613	12	15.9
CRT, Tripureshwar	SCD pg	1	2	Natural	Jan 23-24, 2002	Radish	608	12	15.9
CRT, Tripureshwar	SCDpg	1	2	Natural	Jan 25-26, 2002	Radish	744	12	13.1
CRT, Tripureshwar	SCDgg	1	2	Natural	Jan 23-24, 2002	Radish	608	11	17.7
CRT, Tripureshwar	SCDgg	1	2	Natural	Jan 25-26, 2002	Radish	744	11	14.4
CRT, Tripureshwar	SRDpg	1.6	4	Natural	Jan. 31 and Feb. 01, 2002	Radish	746	13	14.1
Malekhu, Dhading	HSBRD	4.2	10	Natural	March 8-9, 2001	Fish	265	11	9
Bijulibazar, Kathmandu	STD	24	70	Forced (373W)	Oct 12-13, 2002	Masyaura	602	10	19.7
Bijulibazar, Kathmandu	STD	24	70	Forced (373W)	Oct 22-23, 2002	Tomato	743	11	21.6
RECAST, Kirtipur	SCD	1.2	4	Natural	Apr. 21-22, 1998	Cauliflower	647	12	22.1
RECAST, Kirtipur	SCD	1.2	4	Natural	Apr, 29-30, 1998	Cauliflower	688	12	21.1
RECAST, Kirtipur	SRD	3	10	Natural	May 08-10, 1998	Banana	688	14	17.7
RECAST, Kirtipur	SRD	3	10	Forced	Jan 07-08, 1999	Carrot (10W)	712	12	19.6
RECAST, Kirtipur	ISRSD	4.2	10	Natural	Jan 16-17, 2001	Apple	610	12	17.3
RECAST, Kirtipur	STD	24	70	Forced (75W)	July 30-31, 1998	Radish	655	12	21.7
RECAST, Kirtipur	STD	24	70	Forced (75W)	Aug 03-04, 1998	Onion	725	11	20.5

$$\text{Overall thermal efficiency} = \frac{(\text{Water evaporated, kg}) \times (\text{Latent heat of evaporation of water, J/kg})}{(\text{Net input energy, J})}$$

The instantaneous efficiency is given by

$$\text{Instantaneous efficiency} = q_{ev} / q_{input}$$

$$\text{Integrated efficiency} = \int q_{ev} dt / \int q_{input} dt$$

The net input energy in the denominator is mainly the incident solar radiation. This is summed up with energy supplied by other sources such as electricity (forced circulation), biomass (hybrid solar dryer) etc., if provided. The amount of radiant solar energy is determined by the intensity of solar radiation during the drying period and surface area of absorber receiving the radiant heat. Here the surface area of the absorber that is exposed to the solar radiation is constant for a particular dryer and thus the thermal efficiency is dependent only on intensity of solar radiation for the whole drying period.

As given in the numerator of this relation the only factor that varies from product to product is mass of water to be removed. This result into the different values of thermal efficiencies for the same dryer while operating with different products as drying materials. Here the latent heat of evaporation of water is assumed as a constant value of 2390 kJ/kg neglecting the small variations with temperature change.

RESULTS AND DISCUSSIONS

The thermal efficiencies of different types of solar dryers for different drying materials and for different seasons of the year have been calculated from the data obtained from field tests by using the relations given above. Details are given below in the table 1.

Table 1 shows that the maximum value of thermal efficiency is obtained for solar cabinet dryer and is found to be 22.1%. This dryer was developed and experimented at Research Centre for Applied Science and Technology (RECAST). The efficiencies for cabinet dryers developed and tested at Centre for Rural Technology (CRT) with glass and plastics as glazing materials have been obtained as 17.7% and 15.9% respectively. Both the dryers were tested under same ambient conditions. These differences in efficiencies might have caused by the optical properties of glass and plastics. This maximum value of thermal efficiency for solar rack dryer has been calculated as 21.4%. This dryer was developed and tested at Institute of Engineering (IOE), Pulchowk Campus, as an experimental prototype. Due to some additional innovative parts like deflector and radiation distributor in this dryer, the value of efficiency measure is quite higher compared with the value of 17.7% for similar dryers developed and tested at RECAST. The efficiency of dryer, with plastic as glazing material, developed and tested at CRT is only 14.1%. These considerable differences in efficiencies might have caused by the variations in design and materials used for fabrication. All these figures are for the dryers operating with

natural air circulation. Another solar rack dryer was tested at RECAST with natural as well as forced air circulation. The corresponding values for efficiencies obtained were 17.7% and 19.6% for banana and carrot, respectively. This difference in efficiencies might have caused by the difference in drying time for the drying materials rather than nature of the air circulation. Other tests had also revealed that there was no significant difference in the value of efficiency with natural and forced air flow. This might be due to their small drying capacity where natural air flow is sufficient enough for the movement of moisture. The amount of water present in the drying material and nature of bond of the moisture with material had also affected the drying efficiency. This type of effect had been observed while drying cocoon and radish. The maximum value of efficiency calculated for solar tunnel dryer developed and tested at RECAST is 21.7% for radish. Amongst the solar dryers that were tested, only one was hybrid solar/biomass rack dryer whose field test efficiency for fish is too low, *ie*, only 9%. This is because the day, the test was performed, was cloudy and almost all the moisture was removed by the heat produced by firewood. In this case, high amount of heat was lost through flue gas from the chimney.

CONCLUSION

- (i) The Calculations of the drying efficiencies based on thermal energy utilization against thermal energy available showed the value of efficiencies rather low, *ie*, in the range of 13 to 21% in the different modes of drying. It could mean that the amount of solar energy was adequate but not fully utilized.
- (ii) The maximum value of efficiency obtained from the calculation is 22.1% for solar cabinet dryer, 21.4% for solar rack dryer and 21.7% for solar tunnel dryer. These are the figures obtained from experiments performed in the research institutions.
- (iii) The efficiency of hybrid solar/biomass rack dryer is found as low as 9%. This is because of the higher amount of heat loss through flue gas.
- (iv) Due to difference in drying period for different drying materials, different values of efficiencies have been found for the same dryer.
- (v) The efficiency of solar drying system is affected by the properties of drying materials *eg*. moisture content, size, shape and geometry as well as ambient conditions *eg*. solar radiation and temperature, relative humidity, velocity and atmospheric pressure of ambient air.

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