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Techno-economic analysis of a roof-integrated solar air heating system for drying fruit and vegetables

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ABSTRACT

The solar air heater was 46 m^2 and recorded a maximum temperature of 76.6 °C. The dryer was loaded with 200 kg of fresh pineapple slices 5 mm thick. The initial moisture content of 82% was reduced to the desired level (<10%) within 8 h. The performance of the dryer was analyzed in detail by three methods namely annualized cost, present worth of annual savings, and present worth of cumulative savings. The cost of drying 1 kg pineapple worked out to Rs. 11 which was roughly half of that of an electric dryer. The payback period worked out to 0.54 year, much less than the estimated life of the system (20 years).

1. Introduction

Solar drying is considered as one of the most promising techniques for food preservation [1]. Drying of farm produce is an energy intensive operation, and improving energy efficiency by only 1% could increase the profits by 10% [2]. Escalating price of petroleum products and the shortage of fossil fuels have led to increased emphasis on using solar energy as an alternative energy source especially in developing countries like India. Apart from the rise in energy costs, legislation on pollution and sustainable and eco-friendly technologies has created greater demand for energy efficient drying processes in the food industry. The food processing industries can have economic savings by avoiding wastage of costlier energy. Post-harvest losses in the developing countries are estimated to be 30–40% in the case of fruit and vegetables [3].

The solutions involving solar energy collection devices or solar dryers have been proposed to utilize free, renewable and non-polluting energy source provided by the sun. Solar dryers can reduce crop losses and significantly improve the quality of the dried product [4]. However, solar drying systems must be properly designed to match particular drying requirements of specific crops, which can increase the efficiency of a system [5].

Flat plate solar air heaters are now successfully used to heat air for many industrial and domestic applications such as drying farm produce, dehydration of industrial products, and space heating [6,7]. Solar energy plays an important role in low-temperature thermal applications, since it replaces a considerable amount of conventional fuel. Flat plate collectors are, therefore, the best candidates for heating air. The use of air as a working fluid in a solar collector eliminates the need for a heat exchanger, generally employed to transfer heat from liquid to air in a liquid flat plate collector. The air heated in a solar collector can be used more effectively for controlled drying. A solar air heater may supply hot air to a conventional dryer, or a special design may combine the heater and a drying cabinet [8,9].

All designs of solar air heaters developed so far can be grouped into two categories, namely those with non-porous absorbers and those with porous absorbers. In the first type, the air stream flows not through the absorber plate, but above and/or behind it. In the second type, the air stream flow through the absorber because it is porous and includes slit and expanded metal, transpired honeycomb or overlapped glass plate absorber [10]. Ben Slama et al. [11] tested different air collectors with different-flow pattern using baffles in the air passage area. They reported that the provision of baffle creates turbulence of the hot air carrier and thus increases the collector efficiency. Thus the efficiency is increased by approximately 60% compared to collectors without baffles. Yeh and Chou [12] investigated the efficiency of upward-type baffled solar air heaters with baffles.

Solar drying systems are classified primarily according to their heating modes and the manner in which the solar heat is utilized. In broad terms, they can be classified into two major groups, namely active solar energy drying systems (most of which are often termed hybrid or forced circulation solar dryers) and passive solar energy drying systems (conventionally termed natural circu-

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Nomenclature

C_a	annualized cost of dryer (Rs.) (US$1 ≈ Rs. 45)
C_{ac}	annual capital cost (Rs.)
C_b	selling price of branded dried product (Rs./kg)
C_{cc}	capital cost of dryer (Rs.)
C_{de}	cost of drying per kg of dried product in electric dryer (Rs./kg)
C_{dp}	cost of fresh product per kg of dried product (Rs./kg)
C_{ds}	cost per kg of dried product for domestic solar dryer (Rs./kg)
C_e	cost per kW h of electric energy (Rs./kW h)
C_{fp}	cost per kg of fresh product (Rs./kg)
C_m	annualized maintenance cost (Rs.)
C_P	specific heat of air (kJ/kg °C)
C_{rf}	annual running fuel cost (Rs.)
C_{re}	annual electricity cost for fans (Rs.)
C_s	cost of drying per kg of dried product in dryer (Rs./kg)
d	rate of interest on long term investment
D	number of days of use of domestic dryer per year
D_b	number of drying days per batch
F_c	capital recovery factor
F_s	salvage fund factor
F_p	plate efficiency factor
F_{pj}	present worth factor for *j*th year
F_R	collector heat removal factor
I	intensity of solar radiation (W/m^2)
i	rate of inflation
L	latent heat of water (kJ/kg)
m	mass of water evaporated (kg)
m_1	moisture content (dry basis) (%)
$\dot{m}$	mass flow rate (kg m^{-2}h^{-1})
M_d	mass of dried product removed from solar dryer per batch (kg)
M_f	mass of fresh product loaded in solar dryer per batch (kg)
M_y	mass of product dried in the dryer per year (kg)
n	life of solar dryer (year)
N	payback period (year)
P_j	present worth of annual saving in *j*th year (Rs.)
R	annual running hours of blower and axial fans
S_b	saving per batch for solar dryer (Rs./kg)
S_d	saving per day for domestic solar dryer in the *j*th year (Rs.)
S_j	annual savings for domestic solar dryer in the *j*th year (Rs.)
S_1	saving during first year for solar dryer (Rs.)
S_{kg}	savings per kg in comparison to branded product for solar dryer (Rs./kg)
T_1	inlet temperature (°C)
T_2	outlet temperature (°C)
T_a	ambient temperature (°C)
T_p	plate temperature (°C)
U_L	collector heat loss coefficient (W/m^2 °C)
V	salvage value (Rs.)
V_a	annualized salvage value (Rs.)
W	rated power of electric blower and axial fans (kW)

Greek symbols

η	overall efficiency of the collector (%)
η_e	efficiency of electric dryer (%)
τ	transmittance of the glass cover
α	solar absorptance
$(\tau\alpha)_e$	effective transmittance absorptance product

lation solar drying systems). A typical active solar dryer depends solely on solar energy as the heat source but employs motorized fans or blower to pump air through the product.

In recent years, several designs of solar dryers have been proposed in the developing countries and a good deal of work is still in progress. Sreekumar et al. [13] developed a new type of efficient forced convection indirect solar dryer, particularly meant for drying vegetables and fruit. In this dryer, the product was loaded beneath the absorber plate, which prevented the problem of discoloration due to irradiation by direct sunlight. A few works has been reported in the literature on roof-integrated solar air heating system. Palaniappan and Subramanian [14] reported the fabrication details and economic assessment of a 212 m^2 solar air heating system for tea processing (Fig. 1). The solar air heater was used to preheat the air, which was then further heated by the conventional furnace before being blown into the drier. They showed the solar air heating system reduced specific fuel consumption for tea production from 0.932 to 0.71 kg/kg drier mouth tea (dmt), which represents a fuel savings of approximately 25%. Other roof-integrated solar collector reported in the literature was a solar dryer for herbs and spices drying [15] (Fig. 2). The drying duration of the product for this drier was 3–4 days. None of the studies has been addressed the development and performance of roof-integrated solar air heater for drying applications as full energy delivery unit with a detailed long term economics analysis.

This paper describes the development and evaluation of a 46-m^2 non-porous, underflow solar air heater with a batch type dryer for efficient, uniform, and hygienic drying of fruit and vegetables resulting in products of superior quality. The objective of the present work was to develop an efficient solar air heater with baffles and dry the products with minimum duration. In contrast to the above two models, baffles was placed along the air passage of the solar air heater to increase the air fill factor. The baffles made the air to follow a winding path, thereby, doubling the length of air passage through the collector. In addition to that, a centrifugal blower was used to suck hot air from the air heater and four axial fans were provided in the dryer for uniform circulation and recirculation of hot air through the dryer.

2. Performance equation

The generalized performance equation of any air heater is given by

$$\eta = F_p\left[(\tau\alpha)_e - U_L\frac{(T_P - T_a)}{I}\right] \quad (1)$$

where η is the overall efficiency of the collector, F_p is the plate efficiency factor, τ is the transmittance of the glass cover for direct radiation at normal incidence, α is the solar absorptance of the absorber plate for direct radiation at normal incidence, U_L is the collector heat loss coefficient between the absorber plate and the atmosphere, including allowances for side and rear losses, and $T_p = (T_1 + T_2)/2$.

According to Whillier [16], the above equation can also be written as

$$\eta = F_R\left[(\tau\alpha)_e - U_L\frac{(T_1 - T_a)}{I}\right] \quad (2)$$