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EVALUATION OF A ROOF-INTEGRATED SOLAR AIR HEATING SYSTEM FOR DRYING FOODSTUFFS

A. Sreekumar

Asst. Professor,
Centre for Green Energy Technology,
Madanjeet School of Green Energy Technologies,
Pondicherry Central University,
Pondicherry - 605 014,
INDIA

Corresponding author email: sreekmra@gmail.com

ABSTRACT

The paper describes the detailed techno-commercial analysis done on a 46 m² solar air heating system developed in a food processing industry. The solar air heating system was connected to an indoor drier through a duct. A detailed performance analysis was undertaken on the system by loading with 75 kg of ripe mango flake. The product loaded was uniform in size having a thickness of 4mm. On a clear sunny day, the maximum temperature recorded at the outlet of the solar air heater was 66.9^{o}C. The moisture content of the product loaded in the solar drier reduced from an initial moisture content of 75.0% to 6.46 % in a drying duration of 8 hours. Detailed technical analysis was done on the system by four methods namely annualized cost, present worth of annual savings, present worth of cumulative savings, and payback period. The cost of drying 1 kg mango worked out to be 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).

Keywords: Solar air heater, solar drying, economic analysis

1. INTRODUCTION

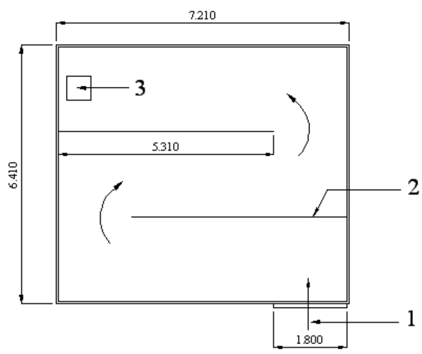
Drying or dehydration of material means removal of moisture from the interior of the material to the surface and then remove this moisture from the surface of the drying material. The drying of product is a complex heat and mass transfer process between the product surface and its surrounding medium and within the product [1-3]. Drying of food products is the most vital operation in the chain of food handling. Proper drying inhibits germination and prevents the growth of fungi and bacteria. It also retards attacks on grains by insects and mites. Traditional drying techniques are specific to each location and commodity; however, these may be categorized as open-air drying, or natural (in-shade) drying [4-5]. In open sun drying, the product is spread in a thin layer on the ground and exposed directly to solar radiation, wind and other ambient conditions. In natural drying, the crop is covered at all times to protect it from the weather. Both these methods are disadvantageous for number of reasons. There is little or no control over the crop drying rate, and it is not possible to ensure uniform drying because of the varying thickness of the piled crop [6-7]. Conventional drying techniques use fossil fuels on large scale to fire the air drier. In many cases, hot combustion gases are passed directly through the products, which often get contaminated by unburned fuel, fumes and soot. Electrical heating of air for drying is preferred, but it is very expensive and not feasible in rural areas of developing countries. Because of energy crisis and intensive energy consumption in the drying process, solar drying is studied widely in many countries in order to make it popular.

Solar drying as a mean of food preservation has been considered one of the most promising areas for the utilization of solar energy. More over India receives intense solar radiation throughout the year. Solar energy can be used with most of the agricultural products as they do not require very stringent drying conditions. Introduction of solar dryers may lead to: (i) the desired reduction of product losses together with improved quality of the dried products, (ii) a significant reduction of drying time, (iii) shortening of the overall harvesting period,(iv) greater returns to farmers by the production of hygienic products [8-14].

Solar dryers are generally classified into two types: "direct type" and "indirect type". In the former type, product to be dried is exposed to direct solar radiation, while in the later type, drying takes place in a closed chamber. Depending on the type of the airflow used, solar dryers can be further classified into "natural circulation" and "forced circulation" systems. In natural circulation dryers, the draft is induced through the natural force called "thermosyphon". In forced circulation dryers, electrically powered fans or blowers, are used to produce air current. This paper describes development and installation of an indirect type 46m^2 forced air circulation solar air heating system for drying fruits and vegetables.

2. DESCRIPTION OF THE SOLAR AIR HEATER AND DRYER

The solar air heating system was integrated with the roof of the building. A south-facing asbestos roof was constructed on the terrace of the building using truss, pillars and beams. The 'underflow' type solar air heater was 6.41m long and 7.21m wide, giving a gross collector area of 46 m^2. The structural frame of the heater was made of extruded aluminium. The absorber plate was made of 38 Standard Wire Gauge (SWG) black chrome copper sheet (absorptivity-0.95), which was screwed to the aluminium frame. The absorber plate was 0.3m wide and was joined each other by using rivets and supported in aluminium square tubes. A rectangular air duct underneath the absorber was formed by providing a rear plate (bottom plate) at a spacing of 10 cm to each other. Three baffles were provided in the air flowing area in order to increase the air fill factor. Each baffle was 5.37 m long, and thus extended to occupy 75% of the collector's width. The baffles were screwed to the bottom plate and their top edge was in contact with the absorber plate. The baffles caused the flowing air to follow a winding path, effectively doubling the length of its passage through the collector. The baffles created turbulence, making the air to flow in close contact with the absorber and decreasing the thermal sublayer. The outer body of the whole structure was covered with aluminium sheet. Figure 1 is a schematic diagram of the air flow through the solar air heater. 24 SWG aluminium sheet was used as bottom plate. The size of the single sheet was 8'x 4' and the whole area was covered by jointing individual sheet. Rock wool insulation was packed sides of copper sheet and beneath and sides of aluminium sheet. On the bottom sides it was spread in between the asbestos sheet and aluminium sheet. The thickness of insulation was 5cm both at the bottom and sides. The whole structure was positioned above the asbestos roof. With a height of 25.4 mm from the absorber plate, 4 mm toughened glass (transmissivity-90%) was mounted using aluminium sections and frames for support. The space between the absorber and the glass reduces the convective losses at the front side. All the possible air leakage from the side and bottom was prevented by silicon sealant.

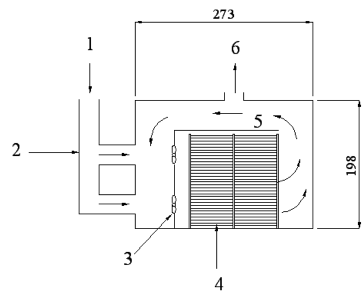


1.Air inlet 2.Metal partition 3.Air outlet to the duct

All dimensions are in metre

Fig. 1 Schematic diagram of the air flow passage in the air heater

The hot air outlet of the heater was connected to a 0.75 kW centrifugal blower through a double-walled Galvanized Iron duct insulated with a 50-mm thick layer of glass wool in between. The centrifugal blower outlet was connected to the dryer, in which the material to be dried was loaded. The dryer was a batch type, with a drying capacity of 200-250 kg of fresh fruit. A schematic diagram of the dryer is shown in Figure 2. The total volume of the dryer was 7.24 m^3. The frame of the dryer was fabricated using CR square tubes and its inner and outer walls were of Stainless Steel (SS) sheets, separated with an insulating layer of rock wool slab to prevent heat loss through the walls of the dryer.



1.Hot air from solar collector 2.Insulated duct 3.Axial fans 4.Perforated trays 5.Air plenum chamber 6.Moist air out

Fig. 2 Schematic diagram of the dryer

The whole inner, outer walls and trays of the dryer were fabricated using Stainless Steel to make the process hygienic and corrosion free. The dryer consisted of 128 perforated trays in 4 partitions to spread the product into a thin layer. Each tray was 560 mm x 560 mm and it was made up of Stainless Steel sheet. Trays were supported using SS angles, welded with SS square tubes. The diameter of the perforations was 3mm with a pitch of 5mm. The drying chamber was divided into the tray area and the plenum area. The hot air was circulated and recirculated with four axial fans, each with a capacity of 4000 m^3 per hour. The axial fans sucked hot air from the solar air heater through the insulated duct and distributed it uniformly in the dryer. Quantity of air inside the drying chamber was nearly eight times more than that of the air coming from the solar air heater. Moist air from the dryer passed through the exhausts provided at the top of the dryer and a damper was fitted here for controlling the airflow rate. The provision was made to set the temperature using an actuator control mechanism. Whenever the temperature rose beyond the preset value, the damper coupled with the actuator positioned in the duct opened, entering the ambient air to lower the temperature. The design detail of the solar drying system is illustrated in Table 1.

3. INVESTIGATION OF THE PERFORMANCE OF THE DRYER

The instruments, materials, and the method of performance evaluation are described below.

3.1 Instruments

Solar radiation intensity was measured with a calibrated Solarimeter, locally named Suryamapi (make-Central Electronics Limited, SM 201 series), having a least count of 2 mW/cm^2 with an accuracy of 2.5%. Air velocity was measured with a Digital thermo-anemometer model. TA 35 (make-Airflow) with a range of 0.25 to 20 m/s. The accuracy of the anemometer is 3%. A 0.5-HP centrifugal fan was used to make the air flow through the collector. The velocity of the centrifugal blower was adjusted using an externally controlled regulator. The ambient temperature, that of the air inlet and the outlet, and of the top glass and absorber plate were monitored using an LM 35 sensor, accuracy $\pm$ 0.1%. The sensor was connected to a computer using an RS 232 interface through a 16-channel data logger, which records the temperatures at the required points for every minute. Relative humidity of ambient air and of that inside the drying chamber was measured periodically with a digital hygrometer, accuracy 5%. Samples of the product being dried were weighed at hourly intervals using an electronic digital balance ($\pm$ 0.001g). At the end of the drying process, the moisture content of the sample was determined by drying the sample in a hot air oven at 108^{o}C for 24 hours.

3.2. Materials and methods

Mango flake was used for the drying tests, which is locally available in abundance. The fruit rich in sugars, is a perishable product. A dried mango also enjoys a very good market. For the drying tests, each batch consisted of 75 kg ripe mangoes. The initial moisture content of the product was 82%. The fruit was sliced horizontally into 4-mm thick discs before loading the drying trays, no other pretreatment was involved. Other materials processed in the dryer were pine apple, bitter gourd, banana, and tapioca (cassava).

4. ECONOMIC ANALYSIS

The dried products are available in the market as both branded and unbranded items. The unbranded product is cheaper, but it is often of inferior quality and produced under unhygienic conditions. The product has a short shelf life and is often unfit for consumption. Branded products are usually manufactured under hygienic conditions, and find a ready market despite the higher price. The economic analysis done here assumes that the cost of solar-dried product sells at a price comparable to that of a branded product.

Three methods were used for the economic analysis. The first, annualized cost method, compares the cost of drying a product of unit weight with the solar dryer to that of drying it an electric dryer. The total annualized cost of the dryer is divided by the amount of product dried in a year to obtain the cost of drying per unit weight of the dried product. The drawback of this method is that the cost of drying does not fully capture the economics of the solar dryer because the cost of drying varies little over the entire life of the dryer, say 20 years (only cost incurred is the cost required to operate the blower and axial fans), while the case of dryers using conventional energy, the increasing cost of conventional energy increases the cost of drying. Therefore, for assessing the economic benefits of the solar dryer, it is essential to determine the savings over the life of the dryer-which is what the second method, namely the life cycle savings does. In this method, the first step is to determine the savings per drying day for the solar dryer in the base year. The present worth of annual savings over the life of the system is calculated next. If the payback period of the system is short, people will come forward to procure the system, if it is long, even when substantial long-term savings are possible, they will not. Therefore, the third method, namely payback period, was also used. A similar approach was also followed by Sreekumar et al. [15] with relevant equations for economic analysis of a solar dryer for domestic use.

5. RESULTS AND DISCUSSION

All the experiments were conducted from 10.00 am to 4.00 pm. The dryer was loaded with 75 kg sliced mango to study the drying behaviour. The mass flow rate of air through the dryer was kept constant throughout the study. The parameters monitored (such as ambient temperature, solar air heater outlet temperature, and intensity of solar radiation) are shown in Figure 3. The experiment was conducted with a centrifugal blower and four axial fans. The maximum temperature of air monitored at the outlet of the solar air heater was 66.9^{o}C. The high temperature output from the air heater, despite the high air mass flow rate, was due to the copper sheet used as absorber material and the baffles to increase the air fill factor. No attempt was made to control the temperature because we wanted to find out the maximum temperature that the collector can attain. The intensity of solar radiation was 682 W/m^2, when the collector achieved its maximum temperature, which was at 1.00 pm. The maximum temperature monitored in the drying chamber was 61.5^{o}C and it was obviously at this time that the solar output temperature was maximum.

Ambient temperature varied from 33.5°C to 38.5°C. The average efficiency of the solar air heater over a day was calculated at 52.55%.

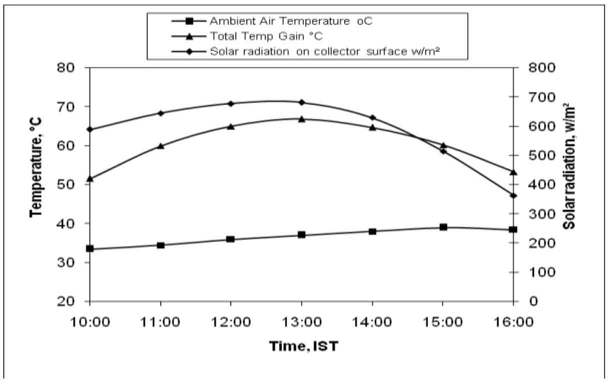


Fig. 3 Variation of temperature outlet of solar air heater with solar radiation

Loading the product had no effect on the solar outlet temperature, because the air heater and dryer were two separate entities connected only by a duct. The maximum rise in temperature (above the ambient) achieved by the solar air heater was 29.9°C. Relative humidity of the air flowing into the dryer varied from 51% to 82% during the study period. The average velocity of air inside the dryer was monitored as 1.2 m/s.

The drying test revealed that the moisture content of the product was reduced from the initial level of 75.0% wet basis (w.b) to the final level of 6.46% (w.b) within about 6 hours (Figure 4). The energy required for removing the moisture from 75 kg of the product was calculated at 235 MJ. The samples were collected from different trays to analyze the uniformity of drying and it was found that the reduction in moisture in all the trays was uniform; the variation was negligible. Drying was rapid initially, but gradually decreased because the surface moisture evaporated quickly at the beginning of the process. It is known that as the moisture content of a product is reduced, more energy is required to evaporate the same amount of moisture from the product. The colour of the dried product is an important parameter to determine the quality of the product. The product retained its original colour in the solar dryer, even after it was completely dry.

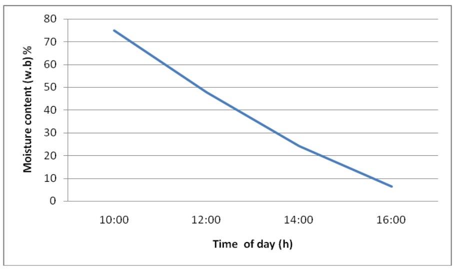


Fig. 4 Reduction in moisture content of the product with time

5.1 Economic analysis

The economic analysis done by the three methods, namely annualized cost, life cycle savings, and payback period are summarized below.

5.1. 1 Annualized cost method

The annual capital cost was calculated first and annual maintenance cost of the solar dryer was taken as 10% of the annual capital cost. The salvage value was also assumed to be 10% of the annual capital cost. The annual capital cost of the solar dryer worked out to Rs. 55,990. A solar dryer can be easily operated for 290 days in a year in countries like India, although number of solar days was taken as 230 for the purpose of the calculation. The dryer was provided with four axial fans, and the running cost of the fans was also taken into account for economic analysis. Annual electricity charges for running the dryers were calculated as Rs. 12000 for the solar dryer and Rs. 8000 for the electric dryer. The high running cost of the solar dryer was due to the blower required to suck hot air from the solar air heater. The total amount of dried product processed annually in the solar dryer was 6666.66 kg and the cost of drying 1 kg of mango slices turned out to be Rs. 11 for the solar dryer and Rs. 19.73 for the electric dryer. The capital cost of the electric dryer, electricity cost per unit, and the efficiency of the electric dryer were assumed as Rs. 275 000, Rs. 4/kWh, and 75% respectively.

5.1.2. Life cycle savings

The cost required for drying 1 kg mango in the solar dryer and electric dryer was calculated. The current saving per day turned out to be Rs. 4773. The cumulative present worth turned out to be approximately 17 million rupees. The investment on solar dryer was Rs. 550 000. Thus, by investing Rs. 550 000 in a solar dryer today, we can save roughly 17 million rupees today. This calculation assumed the life span of the dryer to be 20 years; however the savings were extended over the life of the system.

5.1.3 Payback period

Payback period is the time needed for the cumulative fuel savings to equal the total initial investment. The payback period was calculated to be 0.54 year (equivalent to 191 drying days), which is very short compared to the life of the dryer (20 years). Thus, the dryer will dry the product free of fuel cost with a marginal running cost for almost its entire life period.

6. CONCLUSION

A roof integrated solar air heater with a batch dryer was developed and tested. The drying system proved efficient and economic for drying fruit. The experiments were conducted on mango. The hot air generated from the roof mounted solar air heater was sucked by a blower through an insulated duct and circulated in the dryer located in a room below. Since the product was not directly exposed to solar radiation, the colour of the product was retained even after complete drying. The dryer was loaded with 75 kg mango & drying duration of the product was 6 hours.

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Economic analysis showed that the cumulative present worth of annual savings for drying the product over the life of the solar dryer turned out to be approximately 17 million rupees. The capital investment of the dryer was Rs. 550 000 and the payback period of the dryer was found to be 0.54 year, which is very short considering the life of the system. The cost of drying mango in the solar dryer was only about 20 % of drying it in electric dryer. The life of the system was expected to be 20 years, because the material used in the construction is corrosion proof.

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AUTHOR BIOGRAPHY

Dr. A. Sreekumar is an Assistant Professor at Centre for Green Energy Technology at Pondicherry Central University. He has got above 10 years of research and teaching experience in solar energy. Prior to this assignment, he was working as Asst. General Manager with Cargo Power and Infrastructure Ltd., Ahmedabad. He worked as Head of Solar Division in Sardar Patel Renewable Energy Research Institute, Gujarat. His research interest is in solar thermal energy conversion and thermal energy storage based on latent heat materials. He is teaching solar thermal energy conversion, thermal and electrical systems and energy audit and management for M.Tech students.