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ADVANCED TECHNOLOGIES AND EXPERIMENTAL INVESTIGATIONS IN SOLAR DRYERS: A REVIEW

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Abstract-Solar energy is one of the most important and useful renewable energy sources as it is in abundance and is easily accessible in both direct as well as indirect forms. There are so many uses of solar energy in which solar drying is the significant one. The purpose of drying is to reduce the product's moisture content to a level below which deterioration of product does not occur. Solar dryers of different kind play an important role to preserve different crops for long time within good quality, colour and nutrient content. Fundamentally, there are three types of solar dryers; direct solar dryers, indirect solar dryers and mixed-mode dryers. In thispaper, a review of these types of solar dryers is considered with the characteristic to the product being dried, technical and economical sides. The technical advancement in the development of solar dryers for agricultural products arehigher efficiency, compact design of collector,long-life of drying system and combined energy storage system. The efficiency of solar dryer is also dependent on product size and chemical treatment done on it such as slices are treated with a solution of olive oil and NaOH, decreases its drying time very drastically. Mixed mode solar dryer is found best in all the three types of solar dryers in respect of their efficiency and drying time. Also, Indirect type solar dryer with PCM is found superior than mixed mode solar dryer in respect of efficiency and drying time. For rural areas, where more amount of agricultural products are available for drying process and space is also available easily, greenhouse solar dryer is found best suited to the requirement.

***Keywords*:**Solar Energy**,** Solar Dryer, PCM, Drying Efficiency, Thermal Storage System.

I. Introduction

Continuous instability in the price of fossil fuels, expected reductionin quantity of conventional fossil fuels and environmental concerns causes a drastic increase in potential use of solar energy in agricultural sector. One of the most striking and promising application of solar energy system is solar assisted drying in tropical and subtropical regions. Life of the harvested product can be extended, quality of product is improved, losses are reducedand cost of transportation is reduced, bargaining position of the farmers is improved to maintain comparatively constant price of their product by using solar dryers

More open space area is required for direct solar drying, vulnerable to contamination with foreign materials such as dusts, untidiness as exposed to birds, pest and rodents and also largely dependent on the availability of sunshine. So, the agricultural products which are planned to be stored, must be dried first. Otherwise pests and fungus, which increases in moist conditions, make them unusable.

Availability of appropriate drying equipment which is economically and technically feasible and the lack of awareness of method for agricultural products are the limitations. Only a small number of solar dryers

are commercially available which fulfil theeconomical, technical and socio-economical needs.The technical development in solar drying systems can go on in two directions; first one is having simple structure, low power, short life, and comparatively low efficient-drying system and second one is having higher efficiency, higher power, long life and comparatively expensive[1, 2].Several solar dryers have been developed in the past for the efficient utilization of solar energy.Many experimental investigations and studies have been done for drying of agricultural products using solar dryers.[3, 4]. A number of studies have been done in the tropics and subtropics regions for improvement in solar dryers for drying agricultural products. Fundamentally, there are only four types of solar dryers [5]; direct mode solar dryers, indirect mode solar dryers, mixed-mode dryers, and hybrid solar dryers. From the initial and final moisture content of each product, the energy requirement for drying of agricultural products can be determined. Kiebling [6] has listed a total of 66 different solar dryers, their capacity cost, configurations, and products dried.In Pune (India) a company [7]has moved to commercial drying process using diesel fuel from natural sun drying process. However, fuel heating is proposed to replace by solar drying. For drying of sesame seeds the energy requirements is calculated and the energy supplied through solar heating is calculated. Thus, it was concluded that solar heating provides most of the energy requirement. In thedeveloping countries over 80% of the food product is produced by micro level farmers. They normally practice natural open sun drying process, i.e. products are placed under the sun.

Drying is done by following two steps:-

1) Heat transfer from heating source to the product;

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2) Mass transfer of moisture to product surface from the interior of the product and finally to the surrounding air.

The drying process in ambient conditions is slow and for safe storage the environment of high relative humidity causes insufficient low equilibrium moisture content [4]. For safe drying of agricultural products especially fruits and vegetables the temperature range of hot air is 45^0C to 65^0C. By applying the controlled and specified conditions such as temperature and specific humidity, any type of agricultural products can be converted into the superior quality of dried product.

II.Types of Solar Dryers

Solar dryers are mainly classified into three types, namely (1) Direct mode solar dryer (2) Indirect mode solar dryer and (3) Mixed mode solar dryer.

Direct mode solar drying is the conventional technique of drying the different agricultural products. In this process, the products are directly placed under the solar radiation which releases the moisture content of product to the atmosphere due to the density difference. It is broadly classified into two categories;

(1) The open air solar drying in outdoor;

(2) Covering food stuff with a transparent cover which partially protects it from the rain and other natural phenomena i.e. passive solar drying.

In Indirect solar dryer as name suggests product to be dried is not directly in contact with solar radiation. In this process of drying, heated air is used for drying application which is obtained by passing air through the solar collector on which incident solar radiation falls. This process achieves higher temperature than direct solar dryer and hence efficiency is also better than previous one.

By merging the process involved in direct type solar dryer and indirect type solar dryer, a new process is obtained known as mixed mode solar dryer. In the mixed mode solar dryer as stated above solar radiation directly fall on drying chamber and heated air is also supplied through solar air collector. This type of solar dryer shows maximum efficiency among the above three basic types of solar dryers.

A new type of solar dryer is introduced named hybrid solar dryer. In this solar dryer phase change materials are used for thermal energy storage by virtue of which efficiency of dryer increases to some extent and found to be best suited till now. Thermal storage system used in this type of solar dryer may be of different type such as sensible heat storage system, latent heat storage system or biomass etc. The example of thermal storage system used in the solar dryer are sand, paraffin wax, water, stones etc. In all the above type of thermal storage system the paraffin wax is found to be best suited for dryers as it stores maximum efficiency, and contamination chances by virtue of this is minimum.

A. Direct Solar Drying

In 1976 Everitt and Stanley developed the first solar dryer to avoid open sun drying problem. A box shape of casing unit having a transparent cover for sunlight was made. The deficiency adverted in open sun drying (United States patent) was overcome by this invention using innovative and upgraded method that assisted in fulfilling this purpose. After this many eminent researchers made ever many improvements by employing natural and forced circulation methods, auxiliary sources for heating (electricity and fossil fuels), and energy storage systems to achieve the desired drying properties in solar drying technology.

Lutz et al.[8] developed a solar dryer for multipurpose in drying of several agricultural products which is consist of a tunnel dryer and of a solar air heater. In this dryer the drying time and losses were reduced to great extent with 1 to 3 years of payback period as compared to the traditional open sun drying methods. This system was found very efficient as the requirement of energy for the drying of 1000 kg of grapes was testified to fluctuate between 11.2 kWh to 23.0 kWh depending on the climate conditions and as compared to the additional earning its cost (1.2 US$ to 2.0 US$) was absolutely negligible. However for a particular area broadcasting of solar drying is dependent on the requirements and availability of electricity.

Bena and fuller [9]experimentally investigated a solar dryer for non-electrified location by combining a simple biomass burner with direct natural convection to dry vegetables and fruits. For single layer of 0.01 m thick slices of 20 kg to 22 kg fresh pineapple, the overall efficiency of dryer was reported to be 9%.

Ahmad [10]investigated experimentally a cylindrical collector (5 metre length and 0.36 m diameter) covered withtransparent insulation and having a black interior. A greenhouse dryer was combined with collector to obtain a higher temperature for drying of products. The temperature obtained was about 10^0C higherthe ambient temperature.

Sharma et al.[11] reviewed different solar energy drying systems depending upon design, construction and principle of operation, integrated with recent developments. Theindirect mode solar dryer with forced convection has been found to be superior among the different type of solar dryers, in the context of speed and quality of drying.

El-Sebaii and shalaby[12] emphasized the use of three basic solar dryers; direct, indirect and hybrid solar dryer for drying of agricultural products and different improvements which help to increase the performance of solar dryer.

Fudholi et al.[13] 2010 have reviewed solar dryers in view of technical and economical characteristicsin drying of marine and agricultural products and suggested different modifications in dryers which can enhance the performance of dryer.

B.Indirect Type Solar Dryer

A.A EL Sabaii et al.[14] performed anexperimental study on a solar dryer of anindirect type having natural convection andin which sand is used as a storage material. The drying product is sliced in small parts and chemically treated with a solution of 0.3% NaOH and 0.4% olive oil for 60 seconds after which a drastic change in drying time was seen as it reduces from 60 hours to 8 hours.

Dilip Jain and Pratibha Tiwari[15] performed an experiment on indirect type solar dryer using 50 kg paraffin wax (PCM) which decrease the drying time by increasing the temperature in the drying chamber by 6^0C.

D.K Rabha and P. Muthukumar[16] performed an experimental investigation on a forced convection sola dryer consist of two double pass solar air heater integrated with paraffin wax latent heat storage system and found the overall efficiency of drying system above 10.8%.

Banout et al.[17]developed a double pass indirect mode solar dryer for experimental study on drying of red chilli.Moisture content reduces to 10% on wet basis. Double pass system improve the drying efficiency and quality of dried product as compared to the cabinet dryer.

Rajkotia et al. reported an ideal design for solar dryer having maximum efficiency with the help of CFD tool of ANSYS software by changing different parameter such as the angular solar plate, outlet and inlet area of dryer and reflector plate.

Maundu Nicholas Musemb et al.[18] performed an experimental investigation for mid latitude region of different solar dryers and found that for mid-latitude regions, zenith angle is dependent onsolar declination angle, latitude, day and time of the year and overall efficiency of dryer fabricated was found 17.89%.

Aymen El Khadraoui et al.[19] performed an experimental investigation on thermal behaviour of indirect type solar dryer with PCM and found that temperature of drying chamber is 4^0C to 16^0C higher than ambient all the night and relative humidity is 17% to 34.5% lower than ambient.S.M. Shalaby and Bek[20] performed an experimental investigation on hybrid indirect mode dryer using Paraffin wax (phase change material) as thermal energy storage mediumto dry Ocimum Basilicum and Thevetia Neriifolia and found that the temperature inside the drying chamber was 2.5^0C to 7.5^0C higher than ambient temperature for at least 5 hours after sunset.

N.L.Pawar[21]performed an experiment on natural convection solar dryer for drying coriandrum sativum L. leaves and found that working temperature of natural convection solar dryer varied between 36^0C to 56^0C which provides good efficiency to the dryer of natural convection type.

C. Mixed Mode Solar Dryer

Vinod Kumar Sharma et al. [22]performed an experimental investigation on cabinet type, indirect type and multistacked solar dryers and found that cabinet type dryer was best suitable for small scale and indirect type with multi shelf was found best suitable for large scale drying.

Bolaji and Olalusi [23] experimentally investigateda mixed mode solar dryer for drying chipsof yam. The collector efficiency, rate of drying and percentage of removed moisture (on dry basis) obtained were 57.5%,0.62 kg/h, and 85.4% respectively.

Tarigun and Tekasakul [24] designed a mixed-mode natural convection solar dryer having a biomass burner for drying of agricultural product. The drying efficiency with and without heat storage system was found 23% and 40% respectively. The combined system had uniform drying of product across the tray and an acceptable thermal efficiency.

Fabrice Abunde Neba et al.[25] have performed modelling and simulated design of a novel hybrid dryer and found that it was better than mixed mode solar dryer in respect of efficiency and payback period.

Lalit M. Bal et al.[26] reviewed solar dryerswhich are integrated with latent heat storage system for drying application of agricultural products and found thatwith the use of PCM thetime gap between energy supply and energy demand can be reduced in the solar dryer, thereby it plays a vital role in conservation of energy. Heat loss can be rectify by using a coating of PU foam on inner face of panel in initial model.

Ehsan Baniasadi et al.[27]performed experimental investigation on the mixed mode solar dryer with thermal energy storage system and concluded that performance of solar dryer is improved and drying process time is extended in absence of solar energy.

D. Greenhouse Solar Dryer

W.W.W. Charters et al.[28] reviewed passive greenhouse type solar dryers which are mainly used for agricultural products. They are simple in construction and easy to operate and different design suits different product.Perea Monero et al.[29] experimentally investigated the greenhouse solar dryer for wood chips to use it as a biofuel and found that in 13 days at constant solar radiation of 13.74 MJ/m^2 it can be dried to 10% of relative humidity and can achieve 25.20^{0}C more temperature than direct solar drying.

Prashant Singh Chauhan et al.[30] reviewed on thermal models of greenhouse dryers and found that crop and greenhouse room air temperature, relative humidity inside greenhouse, drying rate, drying kinetics and drying potential can be estimated precisely from thermal modelling and found that performance of forced convection mode solar dryer was found better for crops having higher moisture content and for crops having lower moisture content natural convection mode of greenhouse dryers was found more suitable.

Aymen EL khadraoui et al.[31] performed an experimental investigation and economic evolution on a greenhouse dryer of mixed mode type for drying of red pepper and grapes and found that the moisture content of red pepper by open sun drying was reduced to 16% (wet basis) in 24 hours, whereas the only 17 hours are taken by greenhouse dryer to achieve same moisture content, and for grape moisture content was reduced to 18% (wet basis) in 76 hours in open sun drying, whereas only 50 hours are taken by the greenhouse dryer in reaching to same moisture content level and in comparison of life of the dryer 20 years, payback period of 1.6 years was found very small.

S. Janjai et al.[32] performed an experimental investigation on solar greenhouse dryer having PV ventilation for drying of banana and peeled logan and found that drying time of peeled logan in solar greenhouse dryer was reduced to 3 days from 5 to 6 days which was normally taken in natural sun drying under similar condition.

V.P. Sethi et al. [33]performed an experimental investigation on greenhouse solar dryer using reflection of inclined north wall and found that in greenhouse dryer temperature of air and crop were increased by 1^{0}C to 6.7^{0}C and 1^{0}C to 4^{0}C, respectively and drying time was reduced by 16.67%.

Sumit Tiwari and G.N. Tiwari[34] performed an experimental study to analyse the energy and exergy of a greenhouse solar dryer integrated with a N-PVT air collectorhaving partial covering. They provide mathematical modelling for the system and solve the equations with help of MATLAB.

Sumit Tiwari and G.N. Tiwari[35] have performed an analysis on energy and exergy of mixed mode greenhouse type solar dryer integrated with a N-PVT air collector having partial covering and found that as the number of PVT air collector and mass flow rate increases, exergy efficiency (η_{ex}) and equivalent exergy efficiency ($\eta_{eq,\ ex}$) decreases and Outlet air temperature and greenhouse room temperature increases from 29^{0}C to122.78^{0}C and 22.44^{0}C to 87.42^{0}C respectively, with varying number of N-PVT air collector from 1 to 5 in contrast to 8.8^{0}C to 21.6^{0}C ambient temperature.

Rahul dev et al.[36]performed an experimental study on a greenhouse solar dryer of cabinet type using fibre reinforced plastic(FRP) in walls and concluded that it was better than the greenhouse dryer made of glass or canopy cover also the colour and quality of product can be increased by covering product to be dried by markin cloth.

III.Parameters Generally Reported

In the assessment of solar dryers, the parameters generally taken care of could be categorised as follows:

(i)Physical properties of the dryer

- Type, shape and size
- Area of tray and number of trays (as applicable)
- Drying capacity
- Ease in loading/unloading

(ii)Thermal performance

- Drying rate/drying time
- flow rate of air
- Drying air temperature and relative humidity
- Overall dryer efficiency

(iii)Quality of dried product

- Nutritional attributes
- Sensory qualities (colour, flavour, taste, texture, aroma)
- Rehydration capacity

(iv)Payback period and Cost of dryer

IV.Conclusion

Solar energy in drying application of agricultural products has a large potential from the technical, economical and energy saving point of view. The technical advancement in the development of solar dryers for agricultural products are compact design of collector, higher efficiency, integrated energy storage system and long-life of drying system. In the three basic types of solar dryers, mixed mode solar dryer is found best suitable in respect of drying time and efficiency. But in case of rural area where abundant of space and agricultural product for drying purpose is available greenhouse solar dryer is found best suited to the requirement.

But the evolution of hybrid type of solar dryer (having thermal energy storage system) makes it best suitable than all other type of solar dryers currently commercially available, as it has highest efficiency and lowest drying time. In this type of solar dryer different type of phase change materials (PCM) can be used such as sand, water, stones etc. but paraffin wax is found best suitable material for thermal storage as it provides maximum efficiency than all the other materials. Water-based solar collectors can also be used in place of air-based solarcollectors and water to air heat exchanger can also be used.

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