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A Review of the Recent Developments on Solar Dryers

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ABSTRACT

Solar dryers are used for drying applications of agricultural food products. Use of solar dryers helps to remove moisture from the product and helps to prevent and store for a long duration. In recent days, different drying models have been proposed. In this study, survey of the important drying systems like direct mode dryers, indirect mode dryers and mixed mode dryers is carried out. Also typical dryers like cylindrical dryer, tunnel dryers are studied. Analysis such as exergetic analysis, numerical investigation of dryers are also studied. Mixed mode dryers are simple to design, indirect mode dryers are preferable where, and direct exposure of product to sun's light is not preferable. Mixed mode dryers are always superior in performance. In some of the drying systems, heat storage materials were used. It is observe that, solar dryers gives better performance than open sun drying.

Keywords: *Solar energy, Solar dryers, Heat storage materials.*

1. INTRODUCTION

Earth's surface receives enormous amount of solar radiations and if it utilise properly, helps to meet world's energy demands. Solar energy finds wide range of applications like solar water heating, solar power generation, space heating, dryers, distillation, and solar cockers.

Solar drying is a one such application and this is an effective technique to reduce loss of food products (or Agricultural products) during post harvesting periods. Drying removes the moisture from the food products and helps to store food stuff for a long time.
Generally drying is done by spreading products over the ground, moisture evaporation takes place due to heat of the sun's radiations and flow of atmospheric air over the products [1]. This is an easiest and economical way to remove the moisture from the products. But this methods suffers from many drawbacks like no control over the drying process, dust may enter, damages may occur by animals and birds etc..These disadvantages can be overcome by the use of properly designed solar dryers. Solar dryers are mainly classified as direct mode, indirect mode and mixed mode dryers. In direct mode soar dryers, sun's radiations directly incident on the products to be dried. In indirect mode dryers, sun's radiations are not allowed to incident on the products. Here a separate collector (like Flat Plate Collectors) is used to heat air and then air enters into the drying cabin. In mixed mode, sun's radiations incident directly on products and also a collector is used to supply hot air into the drying cabin.

2. STUDY OF DIFFERENT SOLAR DRYER MODELS

From the beginning of our civilisation, the method practiced and practicing for drying of agricultural products is open sun drying. This open sun drying is having many advantages and disadvantages. These advantages and disadvantages are mentioned in the introductory part. The open sun drying depends on different parameters. Researchers [1] studied and discussed many thermal aspects of open sun drying of various crops like green chillies, green pea, onions, potatoes, and cauliflower. The convective heat transfer coefficient for some crops (green chillies, potato slices, cauliflower, onion flakes, and white gram) also determined and come to conclusion that value of heat transfer coefficient varied significantly with type of crop. This is mainly due to porosity, shape, size and initial moisture contents of the crops. They developed a mathematical model to predict the crop temperature, rate of moisture removal, solair temperature for a steady state conditions. To overcome the disadvantages in open sun drying, solar dryers have been developed in many countries. Researchers from different countries proposed different dryer models and discussed for its performance. Fabrication of solar dryers is very simple, because these can be easily fabricated by using low cost materials which are available in local market. Researchers [2, 3] developed direct mode solar dryers by using low cost materials. The dryer designed [2] was a passive solar grain dryer for domestic applications by using locally available materials such as, plywood, perplex glass, wire mesh angle iron, paints. Fig. 2.1 shows the schematic diagram of this type of dryer. The dimensions of the dryer is 100 × cm 50 cm × 84 cm. Tests were conducted under the metrological conditions of Nsukka, Enuga State, Nigeria.

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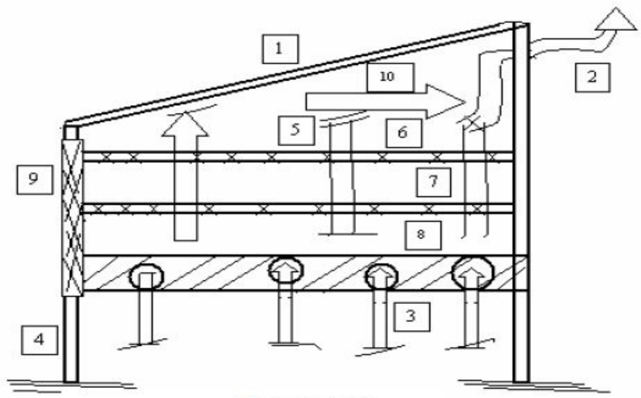
Design procedures like declination, optimum slope, collector efficiency, dryer efficiency are explained clearly. There were two trays used in this system. Upper tray shows better performance than the tray which is placed below that of upper tray. This is because of upper tray receives maximum direct radiations and there was always shading effect on lower tray. Maximum drying temperature obtained was 67 ^{0}C was observed. For drying of pepper, drying time taken was five days and for ground nuts it was eight days. The maximum dryer efficiency obtained was 22 %.



Components

1. Top Glass Cover
2. Chimney
3. Air Vent (in)
4. Iron Stand
5. Side Glass Cover
6. Tray 1
7. Tray 2
8. Wooden Cover
9. Dryer Door
10. Air Flow

Fig. 2.1 Schematic diagram of direct mode passive dryer [2]

This type of dryer is well suited for low temperature drying applications. Another direct mode passive dryer [3] has developed with an facility to vary the collector inclination angle with season and location. It was designed in a way that the angle of inclination of the collector could be varied depending on the location and season. Fig. 2.2 shows the direct mode passive dryer. Materials used to fabricate this dryer were locally available materials. This study explains design procedures such as volumetric air flow, wind flow, weight of moisture removed, declination etc,. Yam was used as test sample. To reduce the moisture from 62 % to 11.11 % for 2160 grams 26 hour required against 36 hours in open sun drying. This study gives the following results; Dryer increases the rate of moisture evaporation, use of dryer needs less attention as compared to open sun drying, any type of products can be dried by using this type of dryer.

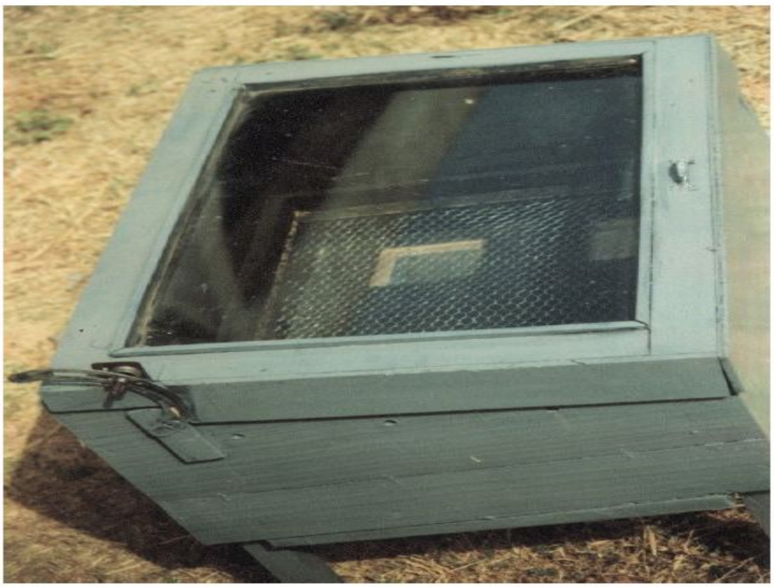


Fig. 2.2 Pictorial view of direct mode passive dryer [3]

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The above discussed dryers are simple to design and fabricate. Similar dryers [4, 5] have been reported for drying fishery products [4] and tropical crops [5]. These direct mode dryer are best suited for low temperature (40^0 C – 60^0 C) drying applications.

A typical cylindrical section drying chamber [6] has developed and a flat plate collector (Air heater) is used. This collector system consists of galvanised steel sheet as absorber. The absorber plate is fixed in a aluminium frame with all sides and back with 5 mm mineral wool insulation to reduce conduction and convection heat losses. A glass cover of 0.4 mm thickness is fixed on the collector to reduce radiation losses. The distance between absorber plate and glass cover is 4 cm. cylindrical drying chamber was made of glass having length 1m and diameter 1m. The solar collector system was faced south at an angle 45^0 with horizontal. Three aluminium trays were used and distance between trays was 0.2 m. A fan was employed for air circulation. This is designed for the drying of 70 kg of bean crop. The experiments were conducted for three air flow rates (0.0405 Kg/S, 0.0540 Kg/S and 0.0675 Kg/S). This system has installed at Zaafaraniya - southwest, Baghdad (Coordinates:33°16'6"N 44°29'41"E).The experiments were started at 8:00 am and stopped at 16:00 pm. fig. 2.3a shows schematic diagram and fig. 2.3b shows the energy flow diagram of solar collector system.

The obtained results shows that, maximum outlet temperature of collector was 71.4 ^{0}C for radiation intensity of 750 W/m^2 with air flow rate of 0.04015 Kg/S. Minimum temperature obtained was 40 ^{0}C for radiation intensity of 450 W/m^2 with air flow rate of 0.0675 Kg/S. The obtained results show that, collector efficiency increases with increase in mass flow rate of air. The highest average collector thermal efficiency obtained was 25.64 % for the flow rate of 0.0675 Kg/S and 18.63 % for the flow rate of 0.0405 Kg/S.

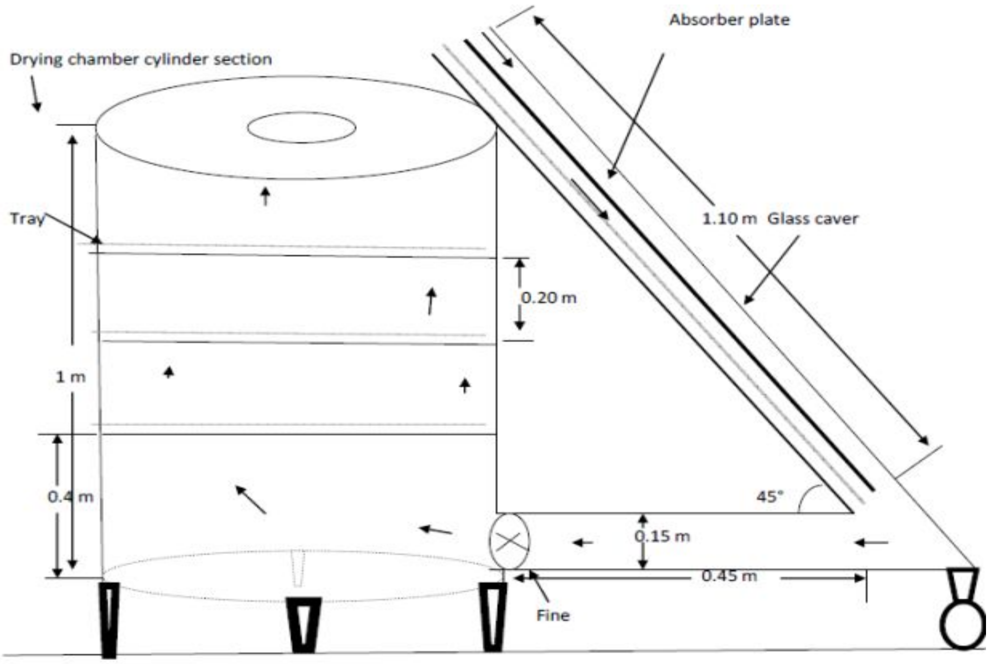

Fig. 2.3a Schematic diagram of cylindrical dryer [6]

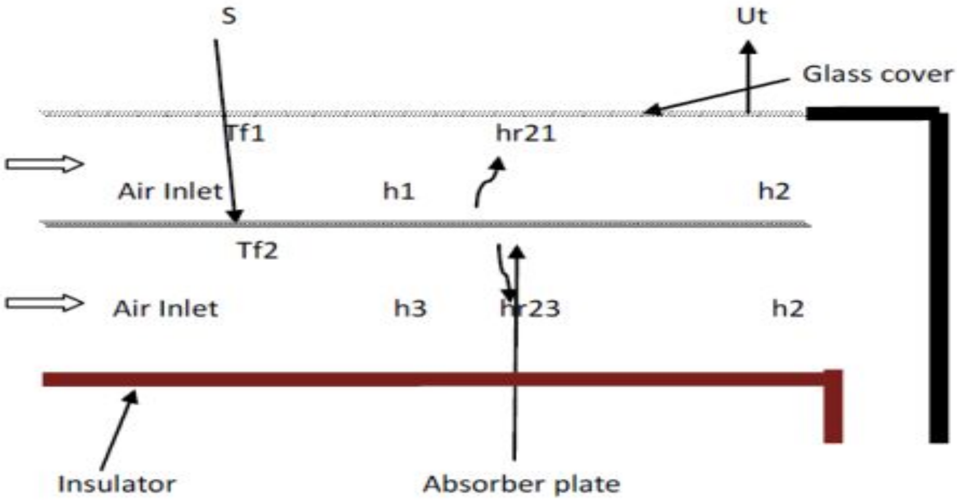

Fig. 2.3b Energy flow diagram [6]

The main advantages of this dryer are; cylindrical drying chamber receives sun's radiation from all the direction without any tracking mechanism. It helps to remove moisture at faster rates. The disadvantage of this dryer is that, glass chamber do not have mechanical strength like metals. For some of the food products it is not preferable expose directly to sun light. Because of direct explosion to sun's light, there may be chances loosing some of the nutrients, colour, odour etc. For this type of applications, indirect mode dryers are best suited. Because product is not directly exposed to the sun's rays. In this type of dryers, solar air heaters are used to heat the incoming air from the atmosphere. In most of the cases heat storage materials are used to collect the solar energy and to heat incoming air from the atmosphere. Wide variety of heat storage materials are used in different dryers. Gravels were used as heat storage materials in one such drying system [7]. Fig. 2.4a shows the schematic diagram and 2.4b shows the pictorial diagrams of forced convective indirect mode solar dryer used.

The drying chamber is made up mild steel with 2 mm thickness. Dimensional specification of drying chamber is 1 m width, 1m length and 1.5 m height. The drying chamber was insulated with mineral wool of 10 mm thickness to reduce heat losses to the surroundings. Solar air heater (Flat plate collector) with 2 m^2 area used to heat the upcoming air. Copper plate with 2 mm thick is used as the absorber plate and it is coated with black paint to increase the absorption of incident solar radiation. A transparent glass cover is used to reduce radiation losses. The gap between absorber plate and glass cover was 25 mm. This gap was provided for air flow. At the backside of the absorber plate and insulation, 100 mm gap was provided and in this gap sand with aluminium scraps were filled. This acts as heat storage medium and helps to provide hot air during off-sunshine hours. A blower is used to provide forced air flow. The complete system was oriented towards south and tilted with an angle 25^0 with horizontal.

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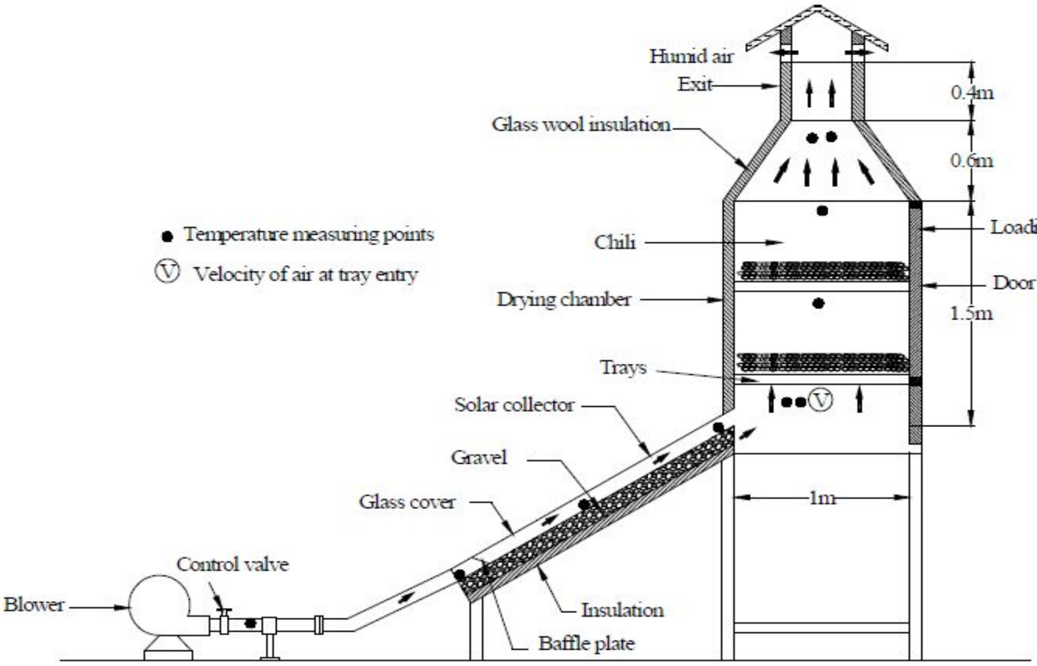

Fig. 2.4a Schematic diagram of indirect mode dryer with heat storage materials [7]

Fig. 2.4b Pictorial diagram of indirect mode dryer with heat storage materials.[7]

The experiments were conducted under metrological conditions of Pollachi, India (latitude of 10.39^o N, longitude of 77.03^{o}E). 40 Kg of chilli was placed in the drying chamber and air flow maintained is 0.025 Kg/S. Fig. 3a shows schematic diagram and fig. 3b shows the pictorial diagram of the experimental setup used in this study. Intensity of solar radiation was measured with solar intensity meter, air velocity with vane type anemometer and temperature at different locations by thermocouples.

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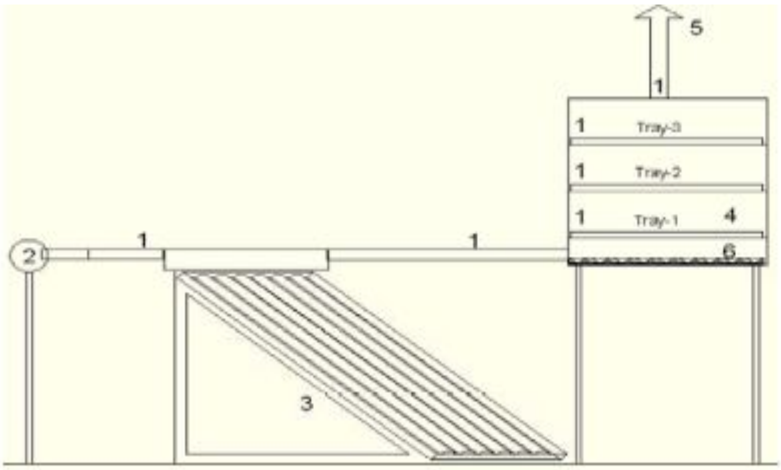
Drying time taken was 24 hours to remove moisture from 72.8% (wet basis) to the final moisture content about 9.1%. Average drier efficiency was estimated to be about 21%. The specific moisture extraction rate was estimated to be about 0.87 kg/kWh. It is reported that higher drying rates were observed during initial stages. This is due to rapid evaporation of moisture at outer surface layer and it gets reduced, because moisture takes some time to migrate from inner surfaces to the outer surfaces and then gets evaporated. The higher temperature was observed inside the dryer than the surrounding temperature and humidity inside the dryer was lower than the atmospheric humidity. Drying rate is depends on the outlet air temperature of solar collector (or inlet air temperature of the drying chamber). It decreases with decrease in outlet air temperature of the solar collector. Higher air outlet humidity was observed during initial stages. These due to higher drying rates were observed during initial stages. Maximum humidity of about 89% was observed during initial stages of drying and was gradually reduced to about 60% at the end of drying. It is also observe that, heat storage material enables to maintain consistent air temperature inside the dryer by absorbing heat and releasing heat. Evacuated tubes were also used in dryers. One such system [8] has been developed. The below fig 2.5 shows the schematic diagram of the evacuated tube drying system.



Schematic diagram of the experimental set-up 1. Temperature sensors; 2. Blower; 3. Evacuated tube collector; 4. Drying chamber; 5.Chimney; 6. Gravel

Fig. 2.5 Schematic diagram of evacuated tube indirect mode dryer [8]

This system mainly consists of evacuated tube solar collector, drying chamber with chimney and a blower. The drying chamber is made of 25 mm stainless steel sheet with dimensions 45 cm× 45 cm 45 × cm. Insulation was provided to all sides by 50 mm thick rock wool slabs. Six evacuated tubes made of borosilicate twin glass with thickness 1.6 mm were used in solar collector. Inner tube is coated with a three layer magnetron sputter coating (SS - Al N/Cu) to reduce heat loss due to convection. Surface area of solar collector is 0.405 m^2. Three aluminium trays were used. Below the trays, heat storage material was placed (Single layer rock bed). Temperature sensors (Resistance Temperature Detector) were placed at different locations to measure the temperature, humidity meter is used to measure humidity, solar radiation intensity is measured by using solar power meter (TES-1333).

Experiments were conducted under the metrological conditions of Thanjavur, Tamilnadu, India. The product used in this study was chilly. Initially experiments were conducted without any heat storage materials. Then experiments were conducted by placing heat storage materials at the bottom of the drying chamber and gravels were used as heat storage materials. This experimental result shows that, dryer with heat storage materials shows better performance than the dryer without heat storage materials. Also comparison made with natural sun drying. Drying of chilli in the designed dryer reduced the average initial moisture content from87.36% to final moisture content of 3.4% in10hours with heat storage material against 12 hours in the dryer without heat storage material and 32 hours in natural sun drying. The designed dryer reduced the duration of drying period up to 66%. The efficiency of the dryer with heat storage material, without heat storage material and natural sun drying are found to be 34.23, 22.03 and 9.32%, respectively. People tried to develop new improve indirect mode drying systems by using new arrangements. In one of the indirect mode dryer [9] sand is used as a heat storage material. In this system the drying chamber is constructed by using wood. Dimensional specification of drying chamber is 1 m ×1 m × 1.5 m. All sides of drying chamber is insulated by 0.04 m foam. Four stainless steel trays were used in the dryer chamber with 0.2 m spacing between each tray. Two heat storage materials chamber (acts as air heater) were coupled to the

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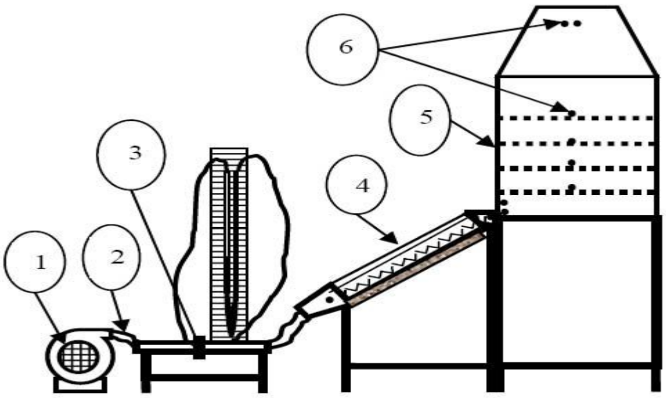
drying chamber. The experiments were conducted for the metrological conditions of Tanta (30^0 47'), Egypt. Temperature at different locations was measure by using temperature sensors and solar radiation intensity by using pyranometer. One set of experiments were conducted without any heat storage materials. And another set of experiments by placing 56 Kg of sand under the absorber plate. Flow rate of air used is 0.0223 Kg/S. After 10 hours of experiments, both the results were compared. Moisture content of grapes reduced from 80 % to 39 % and in case of without heat storage materials and 80 % to 42.4 % in case of with heat storage materials.



1- Blower ,2- Flexible pipe,3- Orifice meter, 4- Solar air heater, 5- Drying chamber, 6- Thermocouples positions.

Fig. 2.6a Schematic diagram of indirect mode dryer with and without heat storage [9]

Fig. 2.6b Pictorial diagram of indirect mode dryer with and without heat storage [9]

It is observed that, use of heat storage materials not shown any significant increase in performance of the dryer. The below given fig. 2.6a and 2.6b shows the schematic and pictorial diagrams of the drying system used in this study.

To obtain higher temperatures and fast drying rates mixed mode solar dryers are preferable. In mixed mode dryers, solar radiations are allowed to incident directly on the drying chamber and at the same time solar collector (Air heater) also receives sun's radiations. Many models of mixed mode solar dryers have been developed. A mixed mode solar dryer systems with flat plate collector[10 ,11] has been developed. In a study [10] absorber plate used is 2 mm thick aluminium sheet. The given fig. 2.7a shows the sectional view of the mixed mode drying system used in that study.

Absorber plate is black coated in order to increase the absorption incident solar radiations. The collector frame is made of wood with 40 mm thickness foam insulation. A transparent glass cover with 4 mm thickness is used to reduce the re- radiation losses. The total area of collector is 0.88 m^2. Well-seasoned wood s used to construct the drying chamber and 4 mm thick glass cover is used. Trays are made of wire mesh.

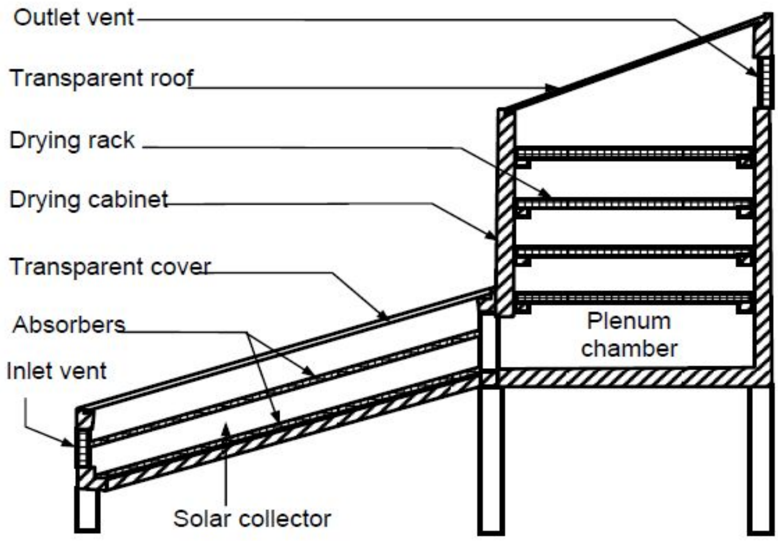


Fig. 2.7a Schematic diagram of mixed mode dryer with flat plate collector [10]

Experiments were conducted for the location of Ado-Ekiti, Nigeria, (7.5^0 N). The complete setup is faced towards south with optimum tilt angle of 17.5 ^{0}. temperature at different locations were measured by thermometers and intensity of sun's radiation are measured by solarimeter. Yam's chips were used in this study. It is observed that, temperature inside the dryer was always greater than the atmospheric temperature. This indicates the prospect for better performance than open sun drying. In this study only free convection tests were conducted. The drying rate, collector efficiency and percentage of moisture removed (dry basis) for drying yam chips were 0.62 kg/h, 57.5 %and 85.4%, respectively. Similar study was made with both free and forced convection [11]. In this system, dryer cabin is fabricated by using 5mm GI sheet, copper sheet with selective coating is used as absorber plate. An electric blower is used in case of forced convective arrangement. Total area of dryer cabin is 1 m^2 and fate plate collector area is 1 m^2. Temperature sensors were used to measure temperature at different locations. Pyranometer is used to measure solar radiation intensity. Potato slices were used in this study as a drying product. Two set of experiments were conducted, one is with free convection (Fig.2.8a) and another with forced convection arrangement (Fig. 2.8b). Experiments were conducted under the metrological conditions of Davanagere (14.31^0 N 75.58^0 E), Karnataka, India. Obtained results shows that forced convective arrangement shows superior performance over the free convective arrangement.

Dryer efficiency obtained in case of free convective arrangement was 5.157 % and in case of forced convective arrangement, it was 7.99 %. Maximum flat plate collector efficiency obtained in forced convective arrangement was 29.26 %. In this study it is observe that, during initial stages higher drying rates were obtained. This is because, during initial stages product contains moisture at outer surfaces of the product and during later stages moisture needs a time to migrate from inner layers to the outer layers to get evaporate.

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Fig. 2.8a Free convective mixed mode dryer with flat plat collector [11]

Fig. 2.8b Forced convective mixed mode dryer with flat plat collector [11]

In another study [12] mixed mode system has been developed. This drying system manly consists of drying cabinet of size 300 mm × 250 mm. Flat plate collector with size 1500 mm × 500 mm was used as solar air heater. Iron sheet is used as absorber material. an electric fan was used for air circulation. To convert mixed mode to indirect mode, a thick polythene cover is used. Temperatures at different locations were measured by using temperature sensors and solar radiation intensity by using pyranometer. The experiments were conducted under the metrological conditions of Shiraz, Iran by taking cuminum grains as test sample. This system was employed in two drying sates (mixed and indirect mode) and four level of drying air flow rates, three active air flow rates (0.084 m^3/S, .127 m^3/S and 0.155 m^3/S) and one passive air flow rate. It is reported that, for drying of cuminum grains, passive flow rate is better than

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that of active flow rates. Efficiency of solar collector is increases with increase in flow rate. Fig. 2.9 shows the mixed mode dryer system used in this work.

Fig. 2.9 Pictorial view of mixed mode passive dryer [12]

Solar tunnel type dryers were also developed by the researchers. One such type of semi cylindrical tunnel type dryer [13] is shown in the given fig. 2.10

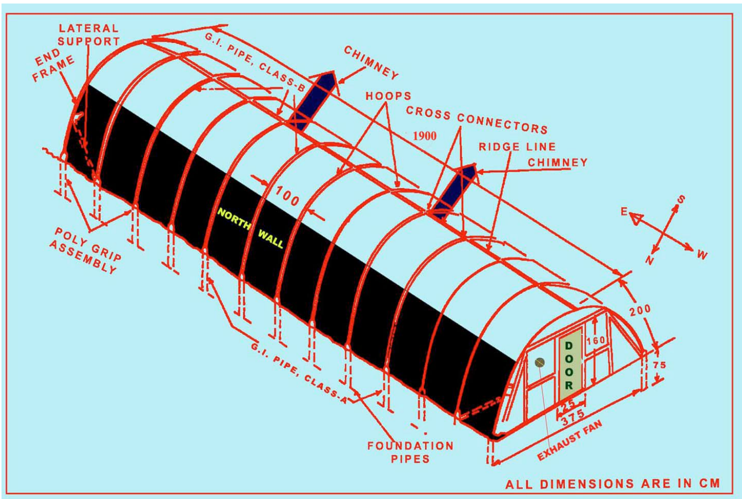

Fig. 2.10 Model of tunnel dryer [13]

In study it is observed that, inside temperature of the solar tunnel dryer was higher than outside by 18^0 C - 22^0C and drying took place in falling rate period. The quality of paper dried in solar tunnel dryer was found to be superior than paper dried in open drying.

A numerical investigation [14] has been carried out for drying of copra in solar tunnel dryer. In this study, roof of the solar tunnel dryer was assumed as semi-circular. Polythene cover was used as cover material. The model used in this study is given in the fig.2.11.

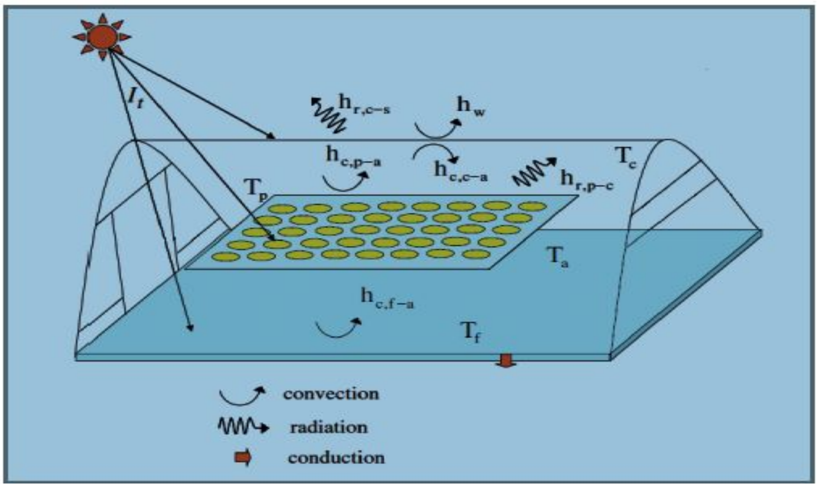

Fig. 2.11 Model of tunnel dryer [14]

The experiments were conducted under the metrological conditions of Semnan, Iran. Numercal analysis was made by using the MATLAB software (*Compaq Visual FORTRAN version 6.5).* The differential equations were developed to describe heat and moisture transfer during the drying process. In this study it is observed that, there is a significant difference in temperatures inside the dryer with the ambient temperatures. The pattern of changes in air velocity inside the solar green house dryer follows the pattern of changes in solar radiation. They also made comparison between actual and simulated values and both results are matching with small percentage of error.

Analysis of different drying systems was also carried out by researchers. An exegetic analysis of three types of drying system such as direct mode, indirect mode and mixed mode is reported [15] Dryers were installed side by side to eliminate the effect of changes in solar radiation and environment. Shelled corn was used as drying product in this study. The results show that, mixed mode and indirect mode solar dryers are more effective than the direct mode dryers. The overall efficiency of mixed mode, indirect mode, and direct mode systems were found to be 55.2%, 54.5%, and 33.4%.

It is observe that final selection of dryer is based on many parameters like physical features of dryer, thermal performance, properties of the product to be dried, economics [16]

3. INFERENCES

From the above study it is observed that, solar dryers are best alternative to reduce the crop losses. Quality of food products dried is superior as compared to quality in open sun drying. Dryer performance is depends on many parameters like type of product to be dried, moisture content, shape of the product, porosity, surface tension, humidity, inlet air temperature, intensity of solar radiation.

Drying process involves heat and mass transfer mechanism. Convective heat transfer co-efficient plays a major role. Value of convective heat transfer coefficient depends on products to be dried and it is different for different food products. Structure of food products affects the process of drying. Internal cells structure different for different crops. Crops which are having loose cell arrangement will allow the moisture to evaporate more rapidly than a crop with closed cell arrangements. Partial pressure of water vapour in the products also affects the process of drying. If atmospheric air is more humid, drying process is normally at lower rate as compared to atmospheric air with less humidity. Another important parameter is intensity of solar radiations, under the condition of good sunny days , it will be possible to obtain good drying rate. During the initial stages of drying higher drying rates are observed. This is because, during the initial stages product contains more amount of moisture at its outer layers. As the drying process proceeds, moisture at outer layers will be completely evaporated and moisture which is present at inner layer will get migrated to outer layer. Simple direct mode dryers are easy to fabricate. This type of dryers are best suited for low temperature drying applications. Indirect mode dryers are preferable where product is not preferable to expose directly to sun’s rays. Mixed mode dryers shows better performance than direct mode and indirect mode dryers. Final selection of dryers is mainly depends on product to be dried, its physical properties, solar radiation intensity, temperature range, economics etc.,

4. CONCLUSIONS

In this present work, study of different dryers was made. Following conclusions are drawn from this study.

a. Crop losses during post harvesting time can be effectively reduced by the use of solar dryers.
b. It is observed that, quality of food product obtained is more superior to the open sun drying.

c. Dryers can be easily fabricated by using low cost locally available materials.
d. Drying process is affected by different parameters like initial moisture content, structure of the product, shape of the product, humidity of atmospheric air, intensity of solar radiations.
e. Use of heat storage materials, Flat plate collectors, Evacuated tube collectors enables the dryer performance.

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