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Review Article

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Utilization of Solar Air Collectors for Product's Drying Processes

Maytham Al-Neama*[1], István Farkas[2]

[1]Mechanical Engineering Doctoral School, Szent István University, Páter K. u. 1., Gödöllő, H-2100, Hungary
[2]Department of Physics and Process Control, Szent István University, Páter K. u. 1., Gödöllő, H-2100, Hungary

Abstract One of the most important applications of solar energy using is air heating generally and solar drying especially. Solar dryers are used mostly for agricultural products moisture content reducing to a level which prevents them to get damage. To classify drying systems, many methods have been discussed in the last studies. According to air movement through the drying system, the dryers classified into: active and passive dryers. Also, based on the construction of these systems, dryers classified into: direct and indirect dryers. There are various computer software which used to design, optimize, describe and estimated the performance of different solar drying systems. Different types of software such as MATLAP, FORTRAN, ANSYS, CFD techniques,…, etc. have been applied for thermal analysis for solar drying systems. The economic viability of solar drying, therefore, depends on the drying cost compared to the market cost. Different criteria have been proposed and applied to characterizing the economical background of solar systems. According to the mentioned classifications above, a literature review has been done with this paper to show the main influential factors and different designs for such systems.

Keywords solar drying, classification, modelling, performance, integrated system, control

1. Introduction

Solar energy has been described as one of the most promising renewable energy sources around world. Along with other forms of renewable energy sources, such as biomass, geothermal, wind, fuel cell and ocean energy, it has a great potential for a wide variety of applications because it is abundant and available always. Direct or indirect conversion of sun energy into other form of energies, refers usually to the thermal collector or photovoltaic cell. The importance of solar energy using for drying applications has been increased due to the changes of traditional energy sources price according to environmental concerns and expectations of conventional sources depletion. Exploitation of solar energy for drying different products can significantly reduce or eliminate product wastage, food poisoning and sometimes improve productivity of the farmers for the sake of better income derived [1].

Drying process is consuming huge amount of energy through the industrial processes. In a lot of industrialized countries, about 7 to 15% of industrial consumption energy for drying process. For example, according to a report that energy consumption for drying processes are ranging from 10 to 15% for United States, Canada, France, and United Kingdome and about 20 to 25% for Germany and Denmark. Most of drying energy consumption has used for paper and pulp industry and it is about 35% [2].

Drying can be defined as a process of water content removal due to heat and mass transfer. It is a technique of different products preservation, which provides longer life, lighter mass for transportation process and smaller space for storage process. Open sun drying is practiced widely in the world, but has some problems such as contamination by dirt and infestation by insects, rodents and other animals. Therefore, the drying process should be happened in closed systems, to get best final product quality [3]. The drying of agricultural items goes back to the beginning of the civilization. The rapid increase in mechanization with high productivity increased the necessity for drying [4]. Drying is used for a wide kinds of products, from cereals to finished goods, from raw materials to by-products. Basically, the processes are depending to the type and quantity of product to dry, the amount of water to remove, the final desired quality of dried product [5].

Drying process of product consists mainly of two stages. In the first stage of drying, the system is considered as a pure material and drying takes place at the surface of the drying material at a constant rate. It is similar to the vaporization of water in the ambient. The mass of the vaporized water depends mainly on external conditions and it is not much affected by the condition of the material. The second stage, drying starts with decreasing drying rate and this type of drying follows constant rate drying. The condition of the second stage can be estimated by the properties of the item being dried [6].

As mentioned before, drying process depends on two types of conditions or parameters; external and internal parameters. These conditions and parameters have been explained in details by Mahendra et al. [7]. Then, Table 1 shows these parameters briefly with their description.

Table 1: Drying parameters [7]

External parameters (properties of moist air)		
Psychrometric chart	Dry bulb temperature	The temperature of moist air specified by an ordinary thermometer.
	Wet bulb temperature	The temperature of moist air specified by a thermometer, the bulb of which is covered with a wet wick
	Dew point temperature	The temperature at which the condensation of water vapour begins if a mixture of air and water is cooled.
	Relative humidity	The ratio of water vapour pressure in the air to water vapour pressure of the saturated air.
	Humidity ratio	The weight of water vapour which is associated with unit weight of dry air.
	Enthalpy	The specific heat of air with water vapour content in it is known as the enthalpy of moist air.
Internal parameters (properties product)		
Moisture content		It is expressed as a percentage of moisture based on wet weight or dry matter.
Equilibrium moisture content		The rate at which the product losses moisture to the surrounding environment is identical to the rate at which it absorbs moisture from the surrounding air, the product is said to be in equilibrium.
Drying ratio		It is a dimensionless number representing the ratio of the weight of wet material entering a dryer to the weight of the same material leaving the dryer.
Latent heat		This property is required to estimate the energy required for evaporation of the desired amount of water from wet product.

Drying is one of the most complicated process of transient transfer of mass and heat with many other processes, such as physical or chemical transformations, which cause changes in item quality as well as the mechanisms of heat and mass transfer. Physical transformations such as shrinkage, puffing, crystallization, glass transitions. Sometimes biochemical reactions will occur result to changes in color, texture, odor or other properties of the dried product.

The use of the solar energy is getting a greater importance in the agricultural drying. At the same time the quality control and quality preservation becomes also more and more importance items for processing of agricultural products than before. In the systems which used solar energy to dry different agricultural products, the moisture content is removed by air which heated by sun arrays energy with temperature range of 50 ^{o}C to 60 ^{o}C. The percentage of moisture content is varies from product to product [8]. Sharma et al. were mentioned the level of safe moisture content for different products items and maximum allowable temperature during drying process, as given in Table 2 [9].

Table 2: Initial, final moisture content and maximum allowable temperature for some products [9]

No.	Crop	Initial moisture content (% w.b.)	Final moisture content (% w.b.)	Max allowable temperature (^oC)
1	Paddy, raw	22-24	11	50
2	Paddy, parboiled	30-35	13	50
3	Maize	35	15	60
4	Wheat	20	16	45
5	Corn	24	14	50
6	Rice	24	11	50
7	Pulses	20-22	9-10	40-60
8	Oil seed	20-25	7-9	40-60
9	Green peas	80	5	65
10	Cauliflower	80	6	65
11	Carrot	70	5	75
12	Green beans	70	5	75
13	Onions	80	4	55
14	Garlic	80	4	55
15	Cabbage	80	4	55
16	Sweet potato	75	7	75
17	Potatoes	75	13	75
18	Chilies	80	5	65
19	Applies	80	24	70
20	Apricot	85	18	65
21	Grapes	80	15-20	70
22	Bananas	80	15	70
23	Guavas	80	7	65
24	Okra	80	20	65
25	Pineapple	80	10	65
26	Tomatoes	96	10	60
27	Brinjal	95	6	60

2. Classification of solar dryers

For different drying moisture contents for products in Table 2, generally the drying systems are classified into low and high temperature operated drying systems. In low temperature systems, the moisture of the product is brought into equilibrium level by heated air using proper ventilation. For high temperature systems, usually used for fast drying rate, especially for high moisture contents products [8].

For solar drying systems, different types of dryers are used with different sizes and designs, that is depend on the application and requirements. Usually, solar dryers are classified according many factors [1]:

- air movement method,
- solar contribution,
- air movement direction,
- type of product items to be dried,
- Assembly insulation.

Also solar dryers are broadly classified in three categories according to the solar radiation receiving; direct, indirect and mixed solar dryers. According to the air movement mode through the system, solar dryers can be classified into active, passive or hybrid dryers. Fig. 1 shows the classification of solar dryers with more details.

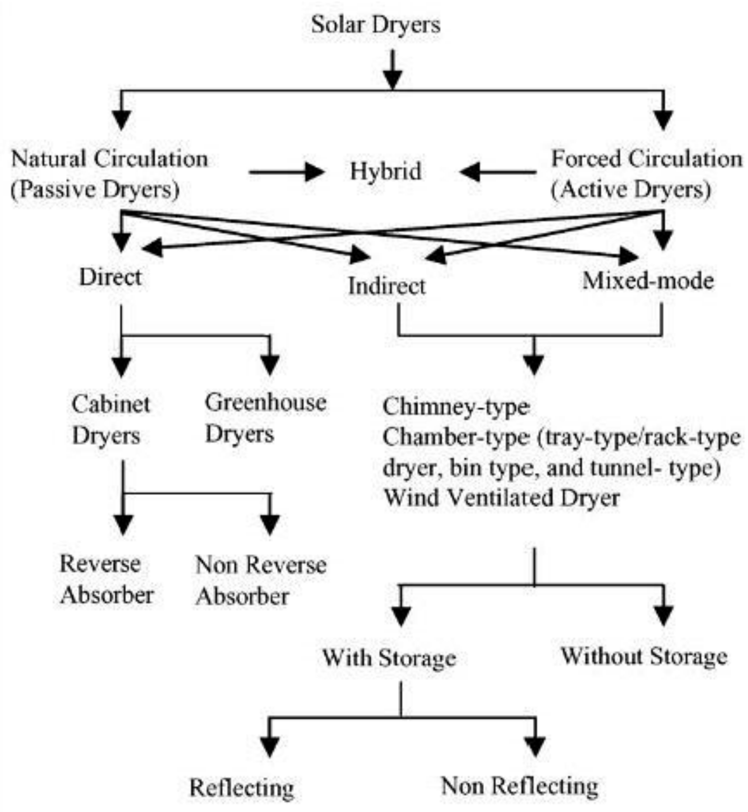

Figure 1: Classification of solar dryers [10]

In forced convection solar dryers (or active solar dryers), the air required for product drying is forced through the solar collector to the dryer chamber using a fan or a blower. In natural convection solar dryers (or passives solar dryers), flow of the air required for product drying is due to natural or buoyancy force action [11].

3. Direct and indirect solar dryers

In a direct solar dryer, the moisture content of the product to be dried is taken away by the direct exposing of solar radiation on the product itself with or without the natural air circulation [11]. A schematic view of direct solar dryer is shown in Fig. 2. Direct solar dryers have a drying chamber which is an insulated external case covered by a transparent cover made of glass or plastic and having many air holes to allow air to enter and exit from the chamber [12] and [13].

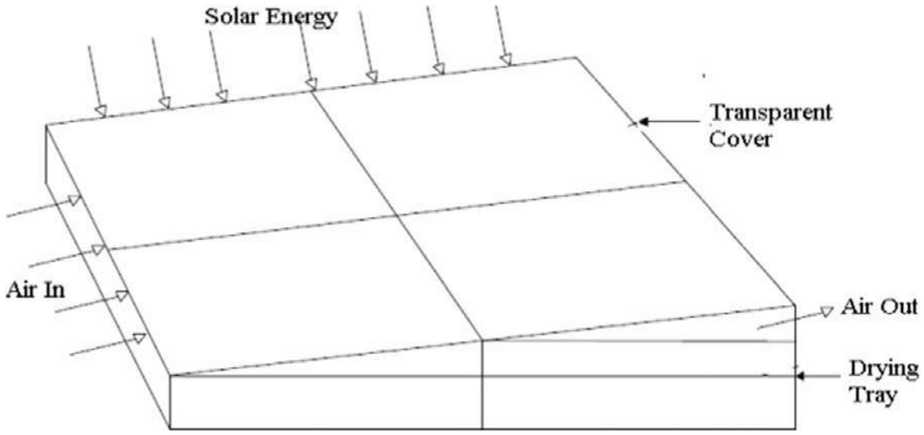

Figure 2: Direct solar dryer [1]

When the solar radiation strikes glass cover, the air heat up and circulates naturally or by wind pressure using external source such as fan, blower,…, etc. or combination of both. A part of solar radiation will get reflected back to the atmosphere as losses whereas the other part will get transmitted inside the dryer cabinet as useful. This transmitted part is reflected back from the product surface and absorbed by it which increases product's temperature and reduces its moisture content by evaporation [9]. The advantages of direct solar dryer, it has a simple design and cheap construction which protects the drying product from dust, rain, debris and dews. But direct solar dryers also have some disadvantages in their performance like product overheating, drying control, undesirable product quality, and limited drying capacity [14].

From many last the literatures, it has been observed that direct solar dryers are the most commonly used devices for drying agricultural and food products. The average drying efficiency of these dryers is varying from 20% to 40% depending on the product item types, air mass flow rate, and the location of drying. The quality of product obtained by direct solar dryers is acceptable and can be improved or enhanced by using some chemical treatments processes.

A multi-purpose solar drying system had been developed, consists of a solar air collector and a tunnel dryer for drying various agricultural items such as fruits, vegetables,…, etc. as shown in Fig. 3. By comparing with the traditional sun drying methods, drying time was reduced significantly by converting solar energy into thermal energy in collector and tunnel dryer. The simple system enables manufacturing either by small scale designs or by farmers using locally available materials. A costs analysis for this dryer shows that the cost payback period ranges from 1 to 3 years, taking into account the reduction in mass losses and the improved quality of the product. Also, the energy costs required to operate the fan of this dryer are negligible compared to the additional earnings from reduced mass losses and improved quality. On the agricultural farming side also showed that the dryer can be easily used by farmers [15].

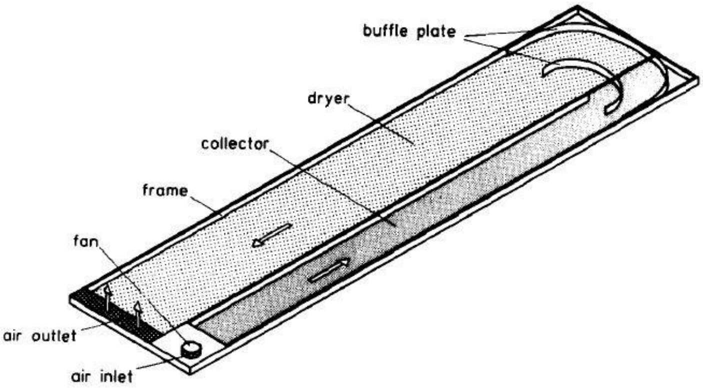

Figure 3: Solar tunnel dryer [15]

Bena and Fuller arranged a direct passive solar dryer with a simple biomass burner to dry different products in non-electrified locations. The overall drying efficiency was reported to be about 9% with a capacity of 20-22 kg fresh pine apple arranged in a single layer of 0.01 m thick slices [16]. Chen et al. studied the drying behaviour of lemon (citrus lemon) slices by developing a closed type solar dryer which consists of a photovoltaic (PV) module as electrical energy source and a dehumidification system to remove the moisture content from the product (fresh lemon slices). However, the photovoltaic module increased the total cost of drying process but it also increased the drying rate significantly. The results indicate that the dried lemon slices using a closed type solar dryer has better general quality levels [17].

A new type of efficient solar dryer for bitter gourd drying had been developed which reduced its moisture contents from 95 to 5% in 6h against 11h for open sun drying as shown in Fig. 4. The dryer has two main components: first for collecting solar radiation energy and producing thermal energy and the second for spreading and protects product items to be dried. The life of the dryer was assumed to be 20 years with a payback period of 3.26 year. The quality of the product dried in the solar dryer was competitive with the available products in the different markets [18].

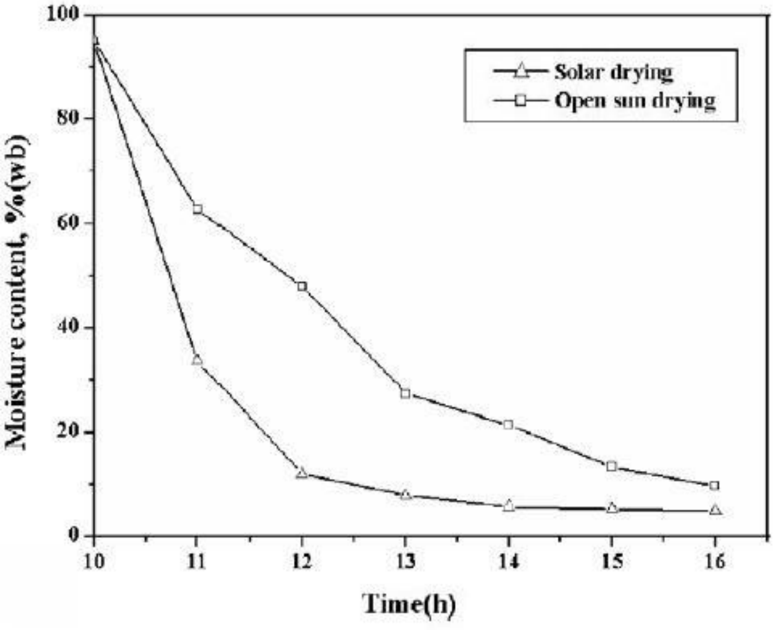

Figure 4: Moisture content with time of drying test under solar and open sun drying [18]

Saxena et al. studied experimentally the increasing of crop drying efficiency by using a PV module. Drying system achieved a higher temperature of 76°C and product moisture content reduction was about 10%.The schematic view of solar dryer with PV cell is shown in Fig. 5 [19]. Also, a free convection solar tunnel drier integrated with rock bed as sensible heat storage material was built to test its performance for copra drying. The drier reduces the moisture content of copra from 52% to 7.1% (wet base) in 54 hours and 60 hours respectively, in two case; with and without heat storage material. The average solar tunnel dryer thermal efficiency was calculated to be about 15%. The use of heat storage material increases the drying efficiency by 1 to 2% [20].

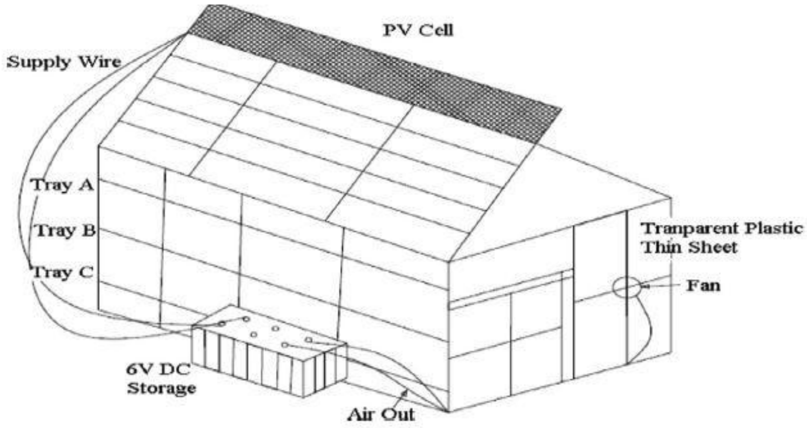

Figure 5: Direct solar dryer with photovoltaic cell [19]

Indirect solar drying systems have a separate drying unit and a solar collector. They are usually consisted from many main components; solar collector, drying unit, a fan if the system is active, and ducting for air circulation through these components [8]. For indirect dryers, the better product drying and optimum system efficiency can be obtained from optimum air mass flow rate. Efficiency of indirect solar dryer depends on the air flow rate across the solar collector which can be controlled by using a fan or a blower. The objective of a fan is to maintain a desired air mass flow rate in the drying unit which results uniform evaporation of moisture from the product [21]. Also the recirculation of drying air can also be employed to enhance drying process effectiveness by utilizing its heat which otherwise wastes in the atmosphere, as the combined solar drying unit which developed [22]. The productivity and efficiency of this unit are increased by 1.5 to 2 times in comparison with the similar drying units due to solar energy accumulation and recirculation of the drying air.

From the general classification of solar dryers as shown in Fig. 1, the both types of solar dryers: direct and indirect can be working with natural, forced air movement (active and passive) or with mixed mode operation.

4. Indirect-passive solar drying systems

In 1999, a modular solar dryer having energy saving feature developed. The effect of various drying parameters especially air flow rate on solar air collector was studied along with the calculation efficiency. The dryer has three main parts: drying cabin, solar air collector, chimney and PV module, as shown in Fig. 6. The modular construction of this system operated with different modes; natural circulation of ambient air, a chimney was planned to strengthen the air flow with the height of 2 m with cross-section of 0.2 m × 0.2 m which is installed in the top of the drying cabin to help this operating mode, artificial circulation of ambient air when the PV module is applied, artificial circulation of the drying air preheated by a solar air collector and also can be combined the above modes [23]. Three years later, a solar drying system developed which had a solar air collector, contains two absorber systems in a single flat plate collector, which was designed according to the psychometric principles. The dryer consists of a flat plate solar collector, wire-mesh absorber, glass transparent cover, chimney and drying cabin. The drying cabin frames and both the collector were constructed from wood sheets. Both the collector was integrated to a drying chamber for food drying. Results showed that the thermal efficiency of flat plate collector and wire-mesh absorber were approximately 21% and 17% respectively with mass flow rate 0.0083 kg/s. The dryer reduced the moisture content of sliced mango from 85% to 13% on wet basis drying. It was found that the dryer was suitable for preservation of mangoes and other kinds of fresh foods [24].

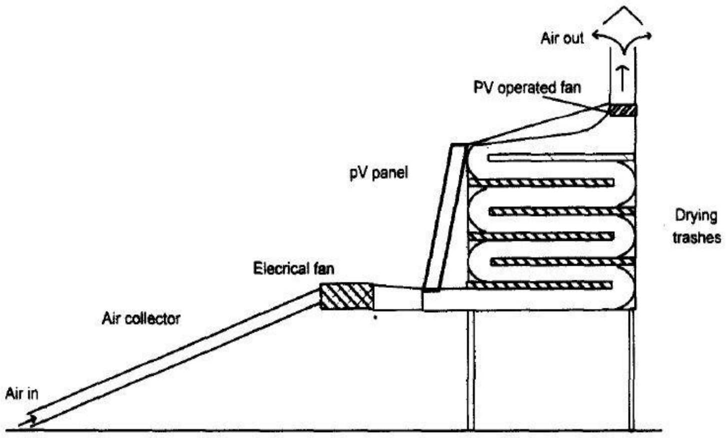

Figure 6: Construction of a modular solar dryer [23]

A two different types of dryers: mixed and indirect natural convection solar dryers had been tested. They reported that, in both configurations, the dryer width is the same as the collector width. The geometry of both dryers is presented with dimensions are width =1.0 m and length =1.0 m. The experimental dryer capacity was about 10 kg which gave a grain depth B, of 0.04 m. In the mixed operation, the drying chamber cover was glass where as in the indirect it was plywood. Air movement through the unit is driven by buoyancy pressure (naturally). The drying cost of the mixed dryer is 12.76 USD/ton and is about 26% lower than the indirect-mode; the quantity of dry grain obtained from the mixed dryer for the whole year is about 2.81 ton and it was less than that from the indirect dryer by 15% [25].

The dryer which shown in Fig.7 consists of an air solar collector, drying chamber, and a chimney had been developed and evaluated. The box-type absorber collector made of a glass transparent cover and black absorber plate was installed with 17.5^{o} tilt angle to the horizontal to get maximum solar radiation at experiments location and to allow the heated air to rise up the unit with little flow resistance. The researcher reported that the heating temperature inside the dryer was higher than the ambient temperature by an average of 15.3 ^{o}C throughout the daylight. Also the efficiency can be enhanced by using box-type absorber solar air collector because the maximum efficiency that obtained was about 60% while those of flat plate absorber and fin type absorber were 21 and 36% respectively [26].

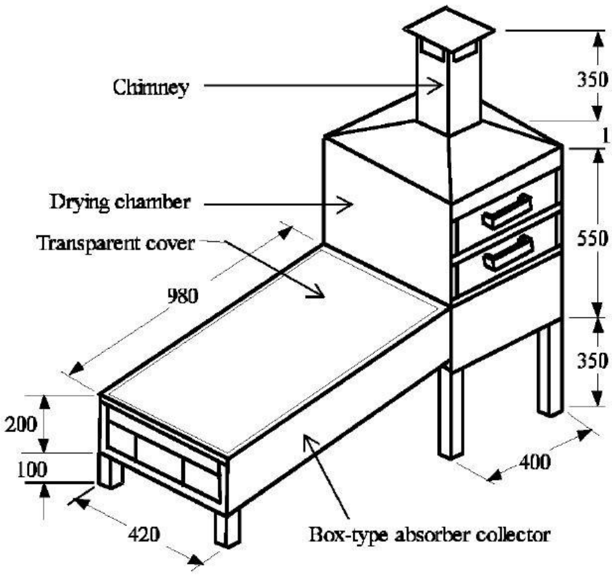

Figure 7: Indirect passive solar dryer [26]

Umogbai and Iorter designed, constructed and evaluated the performance of a passive solar dryer for maize cobs at the College of Engineering, University of Agriculture, Makurdi. The side walls of dryer cabin were made of plywood and coated with white emulsion paint, with an inner drying tray made of wire mesh. The top of the solar collector has made of a layer of 4 mm thick, 100 cm × 70 cm colour less glass sheet which served as the cover transparent plate. A Zinc roofing sheet painted black served as the absorber plate with dimensions; 0.5 mm thick, 100 cm × 70 cm. The results with using about 5 kg of maize cobs reported that the savings in time were achieved as against sun drying as it took 3 days to dry the maize cobs to a moisture content of 13.3% from 30.3% by using the passive solar dryer while it took 6 days to dry the cobs to 13.4% under sun drying. The developed dryer does not use electricity, it can be used by farmers in rural communities [27].

A mathematical model of indirect solar drying system for drying one of the famous dairy product developed and designed in Jordan. The dryer consists of many components; a flat plate solar collector with dimensions of 0.1 m height, 0.8 m width and 1.2 m length, drying chamber consisting of four trays separated from each equally with a distance of 0.2 m. The chamber made of wood with 1 m long. Each tray of dryer has a cross section dimensions of 0.8 m x 0.4 m. The drying chamber design can also be modified to enhance the performance of the drying system, starting by coating the walls with black paint for higher solar radiation absorption or insulate them for less heat losses to the ambient by reflectivity. The total solar radiation on the solar collector surface and drying chamber walls at each hour of the day was also estimated at the 21st of May in Jordan. The mathematical modelling for this simple solar dryer was explained and solved by using engineering equation solver software (EES) [28].

5. Indirect-active solar drying systems

Akpinar et al. developed and presented a mathematical model to study the thin layer drying of apricots in a solar energized rotary dryer with best suitability of Midilli–Kucuk model under drying air temperature ranging from 47.3 to 61.74 °C, air velocity ranging from 0.707 to 2.3 m/s, and rotation speed of column ranging from 0 to 2.25 rpm. An indirect forced convection (active) solar dryer consisting of a solar collector and a rotary column cylindrical drying chamber was used in the experiments. Air heated by the solar air collector was forced through the system by using an electrical fan. On the other hand, the natural sun drying experiments were conducted for the comparison at the same time. According to the results of this study, this model gave the acceptable results and showed good agreement with the experimental data which obtained from the experiments including the thin layer forced solar drying process of apricots [29]. Also an indirect solar drying system of potato has simulated with two different mathematical models. The two models are developed separately; the first estimated the thermal performances of the solar collector with offset rectangular plate fin absorber and the second, determined the kinetics of drying for the data input of the air at the exit of the solar collector. The experimental results of the solar drying system thermal performances, using sunlight in Valenciennes (in the North of France), has been compared with the results that obtained by the theoretical model. The predicted and experimental results were in good agreement [30].

An indirect mode forced solar dryer to dry the fruit and vegetable in Iraq has been constructed and tested. The drying system consisted of three main components are: solar collector, blower and drying chamber. Two air solar collectors with V-groove absorbers, two air passes and single glass cover were used. The total area of collectors absorber is 2.4 m^2.The drying chamber dimensions are width = 1 m, depth = 0.33 m and height = 2 m. The chamber has six separated trays separated by five shelves with 0.3m except the upper one, which is 0.5 m from the roof. Drying chamber walls are made from aluminum plate except the southern side, which was fixed with glass plate. Many types of products were used such as, grapes, apricots, and beans. The results of this study showed that apricots moisture content reduced from 80% to 13% within 1.5 day of drying, grapes moisture content has been reduced from 80% to 18% in 2.5 days of drying and the beans has been reduced from 65% to 18% in 1 day only. The researchers showed that air temperature is the most effective factor on drying rate. The effect variation of air speed inside drying chamber was very small, so can be neglected. Additionally, the relative humidity of output air from the chamber was low between 25 and 30% and therefore there is no need for high velocity air inside drying chamber [31].

An indirect mode forced convection solar dryer integrated with different sensible heat storage material for copra drying had been developed. The drier consists of a solar flat plate air collector provided a heat storage unit, a drying chamber and a centrifugal type blower as shown in figure (Fig. 8). The experiments has done with and without the integration of heat storage materials. Sand mixed with aluminum scrap was used as a heat storage material in solar air collector. The results showed, the specific moisture extraction rate of solar dryer was estimated to be about 0.81 and 0.94 kg kW/h in cases the solar air collector with and without heat storage materials respectively. The results proved also, the time to reduce moisture content of copra from about 52% to about 8% with heat storage materials was about 80 hour, which is mean faster than without using storage materials with drying time 104 hour. The average thermal efficiency of the solar drying system with both drying modes was estimated to be about 23%. The indirect forced convection solar drier integrated with heat storage material is more suitable for producing high quality copra, as can be seen in Fig. 8 [32].

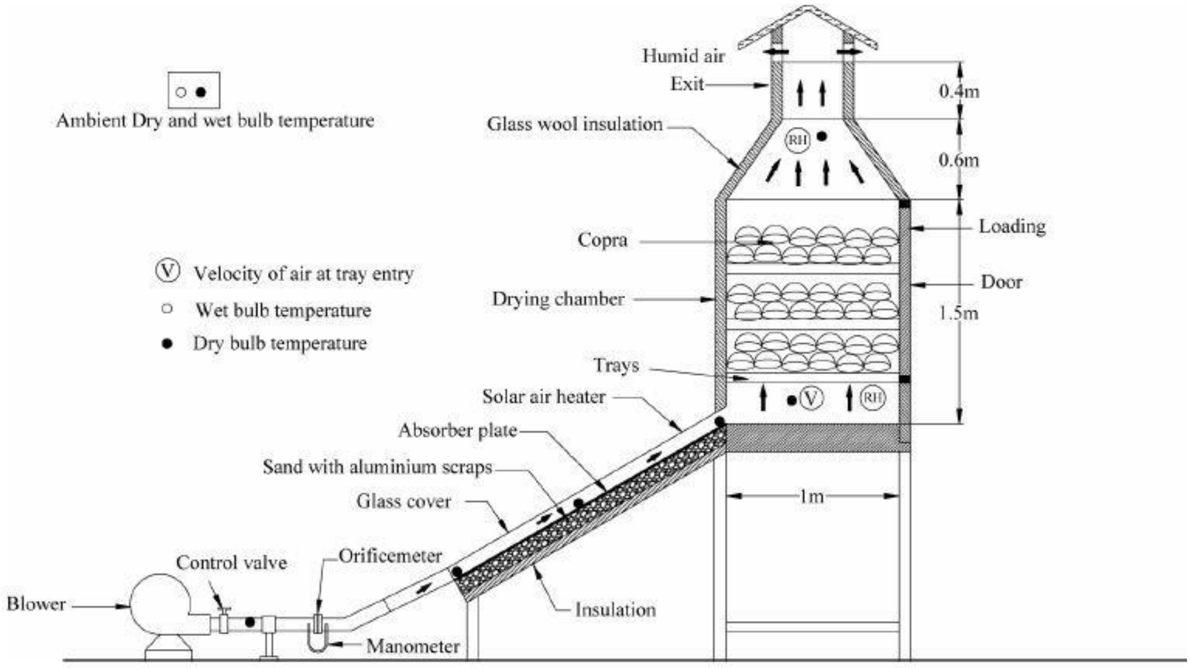

Figure 8: Indirect active solar dryer [32]

A forced convection solar dryer having an evacuated tube collector designed and developed to estimate its performance on bitter gourd in Thanjavur District, Tamilnadu, India. The solar drying system which used, consists of a drying chamber, evacuated tube solar collector, blower and chimney. As shown in figure (Fig. 9) moisture ratio of product is decreased with the time of drying. It is seen that moisture removal is maximum initially and then gets reduced exponentially with time, as because removal of moisture content from the surface first followed by the movement of moisture from internal part of the product to its surface. Also, the moisture content of product reduced from 91% to 6.25% in six hours, so faster than natural direct sun drying as shown in figure (Fig. 10). It can be used to dry different products simultaneously and the products that cannot be dried in natural direct sun drying systems. The most important advantage of using this dryer is it can be used to dry products even during no solar radiation and winter season as it makes use of evacuated tube collector [33].

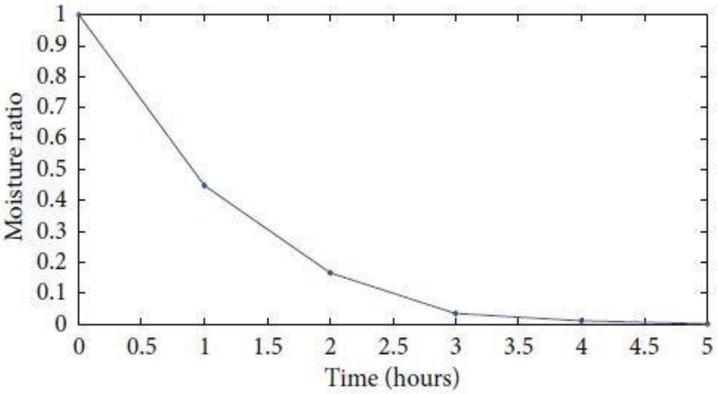

Figure 9: The variation of moisture ratio with drying time [33]

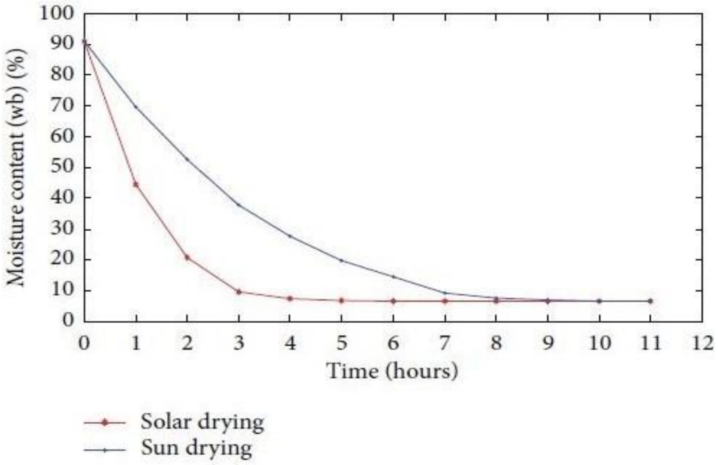

Figure 10: The variation of moisture content with drying time [33]

The behaviour of drying of sponge cotton by using an indirect solar dryer forced convection for different temperatures and air flow rates had been studied. A solar dryer chamber designed and operated for five days of July 2008. The dryer chamber external dimensions are 1.0×0.6×1.2 m^3 and made from the wood. A painted black cylindrical chimney, made from galvanized iron, with 0.4 m height and 0.1 m diameter connected to the top of the drying chamber to increase the speed of air flow. The maximum overall efficiency was observed about 18.6% at air mass flow rate of 0.08 kg/s. The results showed that the temperature of the drying air inside the chamber decreases as it flows horizontally and vertically along the dryer chamber. Additionally, many empirical correlations of temperature lapse and moisture ratio in the drying chamber are found to describe the drying curves of this product according to the basis for the development of solar dryer design charts [34].

6. Integrated solar drying systems

El-Sebaii and Aboul-Enein are developed a solar dryer integrated with a thermal storage system. The dryer tested in two cases, with and without thermal storage. They conclude that the using of thermal storage system reduced the drying time period. During the study solar energy was used exclusively. However, the intensity of solar radiation is sometimes so low that the temperature of the thermal mass may rise by a very small margin above the ambient level, and thereby limiting the continuity of dehydration. Therefore, it is still need to backup the drying process in solar dryers with thermal mass [35]. Bena and Fuller have combined a natural convection solar dyer and a simple biomass burner for small-scale processing of different fruits and vegetables. The capacity of the solar dryer was 20-22 kg of fresh pineapple in a single layer of 0.01 m thick slices targeting the final moisture content of 10%. The energy input from fuelwood was 463 MJ combined with 112 MJ from solar energy. Thus the overall drying efficiency was estimated at 9%. The efficiency of the solar part was found to be 22%, and the efficiency of the biomass burner was 27%. It should be noted that the type of crop and its final moisture content level influences the thermal efficiency. Further modification of the dryer for both the solar and biomass combustion components can improve the overall drying performance. The moisture-removal efficiency varies with the nature and moisture content of the fresh product. Unfortunately, there is lack of standard methods for testing solar dryers which adversely affects their evaluation [16]. Also, Leon et al. recommended the use of the first- and final-day efficiencies for evaluation of drying efficiency [36].

Another type of direct solar-biomass dryer was developed. In this case the biomass burner has a rock slab on the top part which assists in moderating the temperature of drying air. Such dryer designs have a backup heater without thermal storage of captured solar energy. Consequently, the air temperature in the drying chamber drops down to ambient after the sunset requiring backup heating, even when the preceding day was sunny. This leads to wasting of both solar and fuel resources [37].

An indirect type natural convection solar dryer with integrated collector storage solar and biomass backup heaters designed, constructed and evaluated. The dryer was fabricated using simple materials, tools and skills, and it was tested in three modes of operation as solar alone, biomass alone and a combined solar biomass by drying twelve batches of fresh pineapple, with each batch weighing about 20 kg. Moisture and vitamin C contents were determined in both fresh and dried samples. In solar-biomass operational mode, the dryer reduced the moisture content of pineapple slices from about 669 to 11% d.b. and yielded a nutritious dried product. The average values of the final-day moisture-pickup efficiency were 15, 11 and 13% in the solar, biomass and solar-biomass modes of operation respectively. It appears that the solar dryer is suitable for dehydrating pineapples and other fresh foods [38].

In a typical agricultural farm, there is an impetus to maximise collection of all available energy resources, including solar, and distribute them optimally among the different consumers, including dryers, which require a fairly great portion of the total energy. This task requires an integrated solar energy/technology approach [39] and [40]. Setting up a solar preheating system can be economically justified if the solar energy is used throughout the year. The integration of solar energy into the farm energy system seems to be economically possible. However, the storage of the collected solar energy is a key question in such cases. The layout of an integrated solar energy/technology system including a hay dryer is shown in Fig. 11.

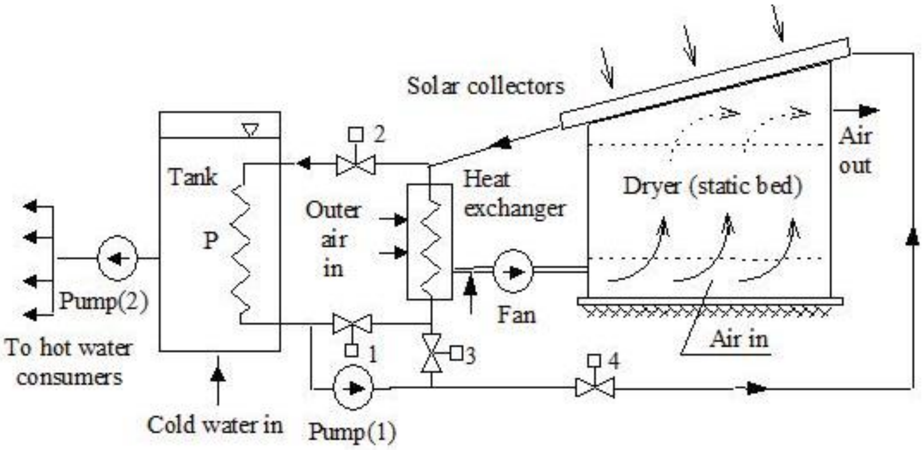

Figure 11: Layout of an integrated solar energy/technology system

The solar collector can be connected by means of the Pump (1) to the drier, to the hot storage tank, to the hot water producing system and to the other technological heat consumer. This gives the advantage of a multipurpose use of solar energy. The Fan forces the air through drying bed, which can also be preheated by oil/gas burner if it is necessary. During night, the storage tank takes over. In this case the drier or other technological heat consumers can be operated from the storage tank by Pump (1) or Pump (2). In case of unfavourable weather conditions additional energy is needed. Such equipment includes oil/gas burners and electrical heating system built into the storage tank. On the basis of the scheme shown in Fig. 11 in conjunction with the operation modes the main categories are: [39] and [40]

1. Drying with ambient air,
2. Drying energy from collector,
3. Collector works for the storage tank,
4. Drying energy from storage tank,
5. Other service from storage,
6. Loading the storage tank,
7. Heating by oil/gas burner.

7. Modelling and simulation of solar drying systems

Based on the last studies, there are various computer software which used to design, optimize, describe and estimated the performance of different drying systems and especially solar drying systems. Different types of software such as MATLAP, Fortran, ANSYS, CFD techniques,…, etc. have been applied for thermal analysis for solar drying systems. The advantages of software using are to save time, to get more accurate results and to give more clear description of the performance.

A physical-mathematical model has been developed to simulate the performance of an integral direct solar dryer. Under operation conditions and based on the heat and mass balance equations, the models has been solved by computer, using the numerical time-stepping scheme. The simulation predicted results have been verified by experiments for drying camomile. The simulated and experimental results showed good qualitative and quantitative agreement such as moisture content percent during drying time, as shown in Fig. 12 [41].

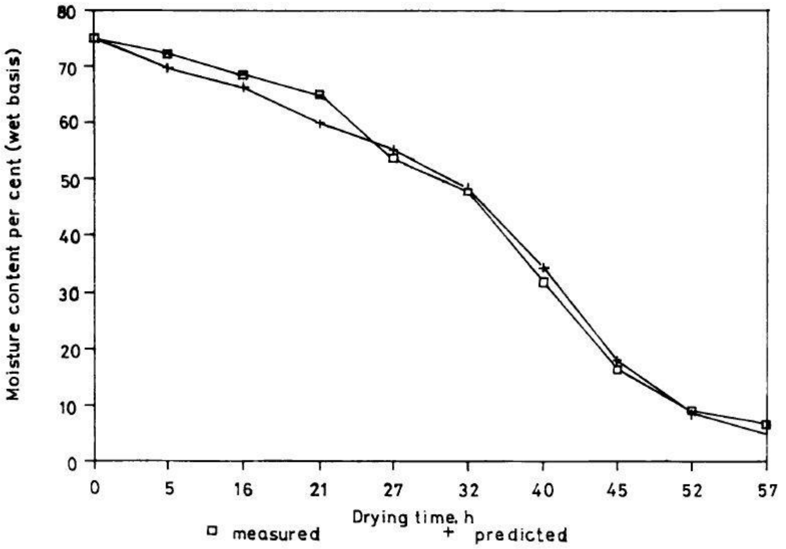

Figure 12: Simulated and measured average moisture contents of chamomile drying [41]

Kumar and Tiwari modelled and validated a natural convection greenhouse drying system used for jaggery. Experimentally, the test has been done separately on 0.75 kg and 2.0 kg of jaggery pieces with dryer dimensions of 0.03×0.03×0.01 m^3. Experiments were carried out from 5 to 8 of February 2004 at Delhi city from 10am to 5pm. To calculate jaggery temperature, greenhouse air temperature and the evaporated water, a computer program was developed with MATLAB software for this purpose. The software program was also used to foretell the thermal performance of greenhouse on the basis of solar intensity and ambient temperature. The developed software was experimentally validated. The results are showed that the analytical (simulated) and experimental results for jaggery drying were in good agreement [42].

An analytical model to study the new concept of a crop dryer integrated with reversed absorber plate type solar collector and thermal storage with natural airflow presented by Jain [43].. A 30^{o} inclined absorber plate with thermal storage and 0.12 m width of airflow channel induced the mass flow rate varied in the range of 0.032–0.046 kg/s during the drying process. The thermal model was developed based on the basic energy balance equations on the various components of the solar crop drying system. The energy balance equations for the components are written based on many assumptions. The mathematical model was solved for Delhi city with latitude 28.35^{o} N, longitude 77.17^{o} E. The climatic conditions during October has been considered because it is a most suitable time for drying most of the crops in India. A MATLAB 6.1 software program has been prepared to solve the mathematical model. The study involved the effect of airflow channel width and packed bed height on the dried crop temperature. The effect of thermal storage had observed on the natural mass flow rate in the drying system. The results obtained that absorber plate with 1 m length and 1 m width with 0.15 m packed bed could dry 95 kg of onion from a moisture content of 6.14 to 0.27 kg water per kg of dry matter in a 24 hours drying time period.

A thin layer indirect solar drying system has been simulated and validated experimentally. This system used to dry mango slices. The prototype of indirect solar dryer was consisted from many parts as shown in Fig. 13: solar collector, drying unit, PVC chimney with 25 cm long and 12 cm of diameter and air recycling pipe. The products items were put inside the dryer on four rectangular trays with 81cm ×44 cm dimensions. Each tray was constructed of wooden frame on which fixed net to facilitate the air flow. The trays were separated with 20 cm to each other. The experiments have been done during three days in harvest season of mangoes. It was observed that a very less constant drying rate in the first day and in the second day it become negligible. For the tree days, the drying rates were reached maximum value of 0.18 g/kg s on the first day, 0.13 g/kg s on the second day and 0.04 g/kg s on the third day. Authors were used MATLAB version 7.0.1 software for simulation mango slices drying process with many assumption has been taken. MATLAB version 7.0.1 has been used to estimate drying rate at regular interval of time by derivation of the moisture content dry basis with respect to time using a derivation program [44].

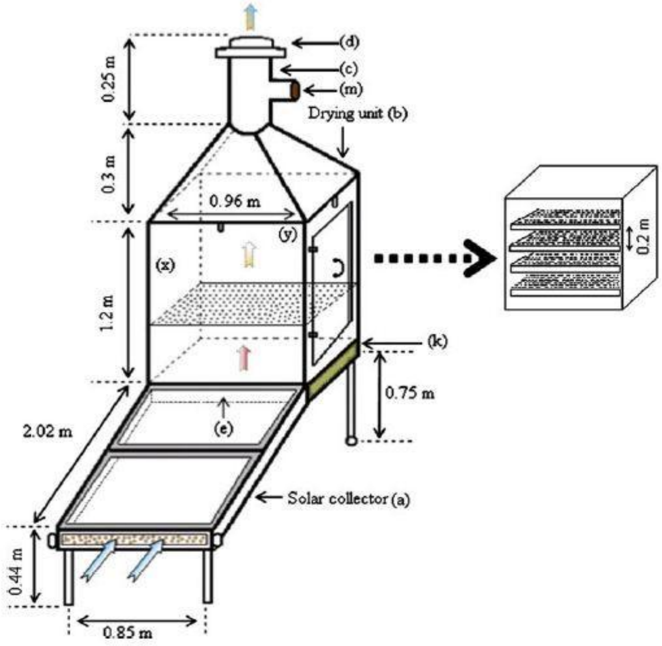

Figure 13: The prototype of indirect solar dryer [44]

The application of artificial neural network (ANN) used for food temperature prediction in a mixed solar dryer. A laboratory test rig natural convection mixed-mode solar dryer has been designed and fabricated to perform the drying experiments on potato samples. The device consisted of an inclined flat-plate air solar collector integrated in series with the drying chamber in which the product items (potato) to be dried is placed on wire mesh tray. The collector and dryer constriction were made of matt black painted aluminum sheet (0.64 mm thickness) used as solar radiation absorber surface with 3 mm thick transparent glass cover on the top to allow solar radiation. Experimental data on potato cylinders and slices obtained for 9 days of different months of the year were used for training and testing the neural network. The climatic variables such as, solar radiation intensity and ambient air temperature are considered as the input parameters for ANN modelling. Results of analysis showed that the network with 4 neurons and logsig transfer function and trainrp back propagation algorithm is the most appropriate approach for both potato cylinders and slices based on minimum measures of error. For cylinder potato, standard error and correlation coefficient for ANN model were 0.208 and 0.952 respectively, for statistical model it was 0.381 and 0.846 respectively. For the slice potato, standard error and correlation coefficient for ANN model were 0.130 and 0.980 respectively and for statistical model were 0.210 and 0.949 respectively [45].

CFD fluent program used to simulate vanilla drying process by indirect solar dryer prototype. The simulated model has been validated with experimental results. Drying system consisted from flat solar collector with dimensions (2.0 m×1.0 m×0.1 m), drying cabinet with dimensions (1.0 m×0.80 m×1.2 m) and 1.2 m chimney with diameter 0.2 m. Solar dryer geometry was made with ANSYS design modeler program with 21° tilt angle of with respect to the horizontal plane was considered for the months from January to March. Comparison between CFD simulated and thermal measured results showed that at solar collector outlet there was a good degree of similarity between measured and calculated temperatures. For drying tests has been obtained 62% reduction in weight, this was a very good reduction in time compared with the time required for the traditional process [46].

Aghbashlo et al. modelled and simulated a deep-bed solar greenhouse drying system used for chamomile flowers drying. For this purpose, a new model containing a phenomenological for the deep-bed drying process of materials has been developed which effectively permits users of the TRNSYS program to design, simulate, and optimize the solar green-house drying system. The model was validated by using previous field trial data for solar greenhouse drying of chamomile in Serbia. The validated TRNSYS model was suitable to simulate the performance of solar drying systems in different locations, predict system performance under different weather conditions and operating conditions, to optimize solar drying system size to match different load profiles, and to develop effective control methods [47].

9. Conclusions

A comprehensive literature review on solar drying systems including different solar dryers, solar air heaters, chimney effect, photovoltaic thermal systems and applications of software in solar drying have been carried out. These studies were showed the importance of drying by solar energy for different products, also it was increasing with time for the features of solar energy. A different solar dryers designs have been showed and the effects of different parameters on drying process performance, the quality of dried products and drying time. The literatures proved that the improving of solar collecting performance will enhance the performance of drying process. The effects of solar chimney and photovoltaic cells have been studied experimentally and theoretically from many authors. The studies showed that temperature is the most effective factor on drying rate for indirect-active solar drying system. Also, the moisture-removal efficiency varies from product to another according to product nature, shape and moisture content of dried product. Moisture removal (%) reduced exponentially with time that is because removal of moisture content from the surface first followed by the movement of moisture from internal part of the product to its surface. Also, the moisture content of product with forced convection solar dryer reduced, so faster than natural direct sun drying.

The feasibility of solar drying must include several additional factors, such as local climate, variety of biological materials, the amount of material to be dried, etc. In addition to the practical issues, the research and development priorities in solar drying are heading in similar directions. The main fields of development are in experimental research, modelling and simulation, long term performance measurements, design, construction, testing and control.

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References

[1]. Toshniwal U. and Karale S.R, 2013. A review paper on solar dryer, international journal of engineering research and applications (IJERA), 3(2), 896-902.

[2]. Bennamoun L., 2012. An overview on application of exergy and energy for determination of solar drying efficiency, International Journal of Energy Engineering, 2(5), 184-194.

[3]. Ertekin C. and Yaldiz O., 2004. Drying of eggplant and selection of a suitable thin layer drying model, Journal of Food Engineering, 63, 349-359.

[4]. Hall C.W., 1980. Drying and storage of agricultural crops, Avi Publishing Co., The University of Wisconsin, Madison.

[5]. Bimbenet J., Bonazzi C. and Dumoulin E., 2012. Drying of foodstuffs, Proceedings of the 13th International Drying Symposium, A, 64-80.

[6]. Can A., 2000. Drying kinetics of pumpkinseeds, International Journal of Energy Research, 24, 965-975.

[7]. Mahendra S., Narendra K., Kumar A., Pradeep K. and Malik M.A.S., 1987. Solar crop drying, CRC press, Florida, USA.

[8]. Kumar M., Sansaniwal S.K. and Khatak P., 2016. Progress in solar dryers for drying various commodities, Renewable and Sustainable Energy Reviews Journal, 55, 346-360.

[9]. Sharma A., Chen C.R. and Lan N.V., 2009. Solar-energy drying systems: A review, Renewable and Sustainable Energy Reviews Journal, 13, 1185-1210.

[10]. Fudholi A., Sopian K., Ruslan M.H., Alghoul M.A. and Sulaiman M.Y., 2010. Review of solar dryers for agricultural and marine products, Renewable and Sustainable Energy Reviews Journal, 14, 1-30.

[11]. Ekechukwu O. and Norton B., 1999. Review of solar-energy drying Systems II: an overview solar drying technology, Energy Conversion and Management Journal, 40, 615-655.

[12]. Ghazanfari A., Tabil L. and Sokhansanj S., 2003. Evaluating a solar dryer for shell drying of split pistachio nuts, Drying Technology Journal, 21(7), 1357-1368.

[13]. Seveda M.S, and Jhajharia D., 2012. Design and performance evaluation of solar dryer for drying of large cardamom (*Amomum subulatum*), Journal of Renewable and Sustainable Energy, 4, 1-11.

[14]. Hii C.L., Jangnam S.V., Ong S.P. and Mujumdar A.S., 2012. Solar Drying: Fundamental, Applications and Innovations, Authors of individual chapter.

[15]. Lutz K., Mühlbauer W., Muller J. and Reisinger G., 1987. Development of a multi-purpose solar crop dryer for arid zones, Solar wind Technology Journal, 4(4), 417–424.

[16]. Bena B. and Fuller R.J., 2002. Natural convection solar dryer with biomass back-up heater, Solar Energy Journal, 72(1), 75-83.

[17]. Chen H., Hernandez C.E. and Huang T, 2005. A study of drying effect on lemon slices using a closed-type solar dryer, Solar Energy Journal, 78, 97-103.

[18]. Shreekumar A., Manikantan P.E. and Vijaykumar K.P., 2008. Performance of indirect solar cabinet dryer, Energy Conversion and Management journal, 49, 1388-1395.

[19]. Saxena A., Agarwal N. and Tirth V., 2011. Performance studies of an improved solar dryer in the climate of Uttar Pradesh, International conference on national solar mission.

[20]. Ayyappan S. and Mayilsamy K., 2012 Solar tunnel dryer with thermal storage for drying of copra, International journal of energy technology and policy, 8(1), http://www.inderscienceonline.com/doi/pdf/10.1504/IJETP.2012.046017

[21]. Ghatrehsamani S.H. and Zomorodian A., 2012. Impacts of drying air temperature, bed depth and air flow rate on walnut drying rate in an indirect solar dryer, International Journal of Agriculture Sciences, 4(6), 253–256.

[22]. Komilov O.S., Astanov S.Kh., Safarov O.F., Sharipov M.Z., Faizullaev A.R., and Tillaev L., 2009. Combined Solar Drying Unit, Applied solar energy journal, 45(4), 262-265.

[23]. Farkas I., Seres I. and Meszaros C., 1999. Analytical and experimental study of a modular solar dryer, Renewable Energy Journal, 16, 773-778.

[24]. Madhlopa A., Jones S.A. and Saka J.D.K., 2002. A solar air heater with composite-absorber systems for food dehydration, Renewable Energy Journal, 27, 27-37.

[25]. Simate I.N., 2003. Optimization of mixed-mode and indirect-mode natural convection solar dryers, Renewable Energy Journal, 28, 435-453.

[26]. Bolaji B.O., 2005. Development and performance evaluation of box-type absorber solar air collector for crop drying, Journal of Food Technology, 3(4), 515–600.

[27]. Umogbai V.I. and Iorter H.A., 2013. Design, construction and performance evaluation of a passive solar dryer for maize cobs, African Journal of Food Science and Technology, 4(5), 110-115.

[28]. Tashtosh G.M., Jaradat M., Zuraiakt S. and Aljarah M., 2014. A mathematical model of indirect solar drying of dairy products (Jameed), 2(1), 1-13.

[29]. Akpinar E.K., Sarsilmaz C. and Yildiz C., 2004. Mathematical modeling of a thin layer drying of apricots in a solar energized rotary dryer, International Journal of Energy Research, 28, 739-752.

[30]. Ali S., Desmons J.Y., 2005. Simulation of a new concept of an indirect solar dryer equipped with offset rectangular plate fin absorber plate, International Journal of Energy Research, 29, 317–334.

[31]. Al-Juamily K.E.J., Khalifa A.J.N. and Yassen T.A., 2007. Testing of performance of fruit and vegetable solar drying system in Iraq, Desalination Journal, 209, 163–170.

[32]. Mohanraj M. and Chandrasekar P., 2009. Performance of a solar drier with and without heat storage material for copra drying, International Journal Global Energy Issues, 31(2), 112-121.

[33]. Sundari AR.U., Neelamegam P. and Subramanian C.V., 2013. An experimental study and analysis on solar drying of bitter ground using an evacuated tube air collector in Thanjavur, Tamil Nadu, India, International conference on solar energy photovoltaic.

[34]. Aissa W., El-sallak M. and Elhakem A., 2014. Performance of solar dryer chamber used for convective drying of spong-ecotton, Thermal Science Journal, 18(2), S451-S462.

[35]. El-Sebaii A.A., Aboul-Enein S., Ramadan M.R.I., El-Gohary H.G., 2002. Experimental investigation of an indirect type natural convection solar dryer, Energy Conversion and Management, 43, 2251-2266.

[36]. Leon M.A., Kumar S., Bhattacharya S.C., 2002. A comprehensive procedure for performance evaluation of solar food dryers, Renewable and Sustainable Energy Reviews, 6, 367-393.

[37]. Prasad J., Vijay V.K., 2005. Experimental studies on drying of Zingiber officinale, Curcuma l. and Tinosopora cordifolia in solar-biomass hybrid drier, Renewable Energy, 30, 2097-2109.

[38]. Madhlopa A., Ngwalo G., 2007. Solar dryer with thermal storage adn biomass-backup heater, Solar Energy, 81, 449-462.

[39]. Farkas I., 2008. Solar drying, Stewart Postharvest Review, 2, 2-8.

[40]. Farkas I., 2013. Integrated use of solar energy for crop drying, Drying Technology, Vol. 31, No. 7, 2013, 866-871.

[41]. Mahapatra A.K., Imre L., Barcza J., Bitai A. and Farkas I, 1994. Simulation of a directly irradiated solar dryer with integrated collector, International Journal of Ambient Energy, 15(4), 195-204.

[42]. Kumar A. and Tiwari G.N., 2006. Thermal modeling of a natural convection greenhouse drying system for jaggery: An experimental validation, Solar Energy Journal, 80, 1135-1144.

[43]. Jain D., 2007. Modeling the performance of the reversed absorber with packed bed thermal storage natural convection solar crop dryer, Journal of Food Engineering, 78, 637-647.

[44]. Dissa A.O., Bathiebo J., Kam S., Savadogo P.W., Desmorieux H. and Koulidiati J., 2009. Modeling and experimental validation of thin layer indirect solar drying of mango slices, Renewable Energy Journal, 34, 1000-1008.

[45]. Tripathy P.P. and Kumar S., 2009. Neural network approach for food temperature prediction during solar drying, International Journal of Thermal Sciences, 48, 1452–1459.

[46]. Romero V.M., Cerezo E., Garcia M.I. and Sanchez M.H., 2014. Simulation and validation of vanilla drying process in an indirect solar dryer prototype using CFD Fluent program, Energy Procedia Journal, 2013 ISES Solar World Congress, 57, 1651-1658.

[47]. Aghbashlo M., Müller J., Mobli H., Madadlou A. and Rafiee S., 2015. Modeling and simulation of deep-bed solar greenhouse drying of chamomile flowers, Drying Technology: An international journal, 33(6), 684-695.