THERMAL PERFORMANCE OF A TRIPLE-PASS SOLAR DRYER

WONG HUI QIN

UNIVERSITI SAINS MALAYSIA

2021

THERMAL PERFORMANCE OF A TRIPLE-PASS SOLAR DRYER

by

WONG HUI QIN

Thesis submitted in fulfilment of the requirements for the degree of Master of Science

March 2021

ACKNOWLEDGEMENT

I would like to acknowledge and express my appreciation to Universiti Sains Malaysia for providing research grants 1001/PFIZIK/814228 and 1001/PFIZIK/814250 that made this research possible. Special thanks to BOH company for sponsoring the tea leaves used in the field experiment.

My deepest gratitude goes to my supervisors, Prof. Madya Nurhayati Abdullah and Prof. Fauziah Sulaiman, for their support, guidance and encouragement throughout the study. My grateful thanks also extended to School of Physics for all kind of facilities and resources that have been supplied during the experimental works. The technical support and assistance from the laboratory assistants, technician and academic staffs are highly appreciated as well.

Last but not least, I would like to express my sincere gratitude to my parents, friends and all the people who had contributed in any form of assistance throughout the research and study.

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

LIST OF PLATES

Page

LIST OF SYMBOLS

A_o	Area of collector outlet (m^2)
A_c	Area of collector (m^2)
Av.	Average value
c_d	Specific heat capacity of desiccant (J/kg °C)
c_p	Specific heat of air (J/kg °C)
DR	Drying rate (kg moisture/ hr)
H_a	Relative humidity of ambient (%)
H_c	Relative humidity of chamber (%)
I	Solar irradiance (W/ m^2)
k	Drying constant (s^{-1})
L_w	Latent heat of vaporisation of water at outlet temperature (J/kg)
m_d	Mass of desiccant (kg)
$\dot{m}$	Mass flow rate (kg/s)
Max.	Maximum value
MC_{db}	Dry basis moisture content (%)
MC_e	Equilibrium moisture content (%)
MC_t	Moisture content at any time of drying (%)
MC_{wb}	Wet basis moisture content (%)
Min.	Minimum value
P_{fan}	Power of fan (W)
Q_i	Incident solar energy (J)
Q_u	Useful energy gain (J)
SHS	Sensible heat storage

SMER	Specific moisture extraction rate
t	Drying time (s)
T_a	Ambient temperature (°C)
T_c	Chamber temperature (°C)
T_{df}	Final temperature of desiccant (°C)
T_{di}	Initial temperature of desiccant (°C)
T_1 or T_i	Collector inlet temperature (°C)
T_2	Absorber plate temperature (°C)
T_3	Temperature of first turning point or end of first pass (°C)
T_4	Temperature of second turning point or end of second pass (°C)
T_5 or T_o	Collector outlet temperature (°C)
u_{total}	Total uncertainty
ν_o	Average air velocity at outlet (m/s)
W	Weight of water evaporated from the product (kg)
W_i	Initial weight of the product (kg)
W_f	Final weight of the product (kg)
x_n	Relative uncertainty of the n^{th} factor
ΔT	Temperature difference between collector inlet and outlet (°C)
η	Collector efficiency (%)
η_{dryer}	Dryer efficiency (%)
η_{inst}	Instantaneous collector efficiency (%)
η_{TH}	Thermohydraulic efficiency (%)
ρ	Density of air (kg/m^3)
ϕ	Porosity

LIST OF APPENDICES

PRESTASI TERMA PENGERING SURIA TIGA-LALUAN

ABSTRAK

Pengeringan hasil pertanian merupakan teknik purba untuk melanjutkan jangka hayat makanan dan mengurangkan kehilangan hasil pasca tuai. Oleh sebab masalah keselamatan makanan global, kehilangan hasil pasca tuai yang serius, kelemahan kaedah pengeringan terbuka dan persoalan alam sekitar dari pengeringan industri, pengeringan suria telah menjadi kecenderungan para penyelidik untuk meningkatkan prestasi sistem pengeringan suria dari aspek yang berlainan. Pengering suria yang sedia ada biasanya direka untuk hasil tanaman yang tertentu dan menghadapi pelbagai kelemahan seperti penukaran sinaran suria yang tidak cekap, suhu pengumpul yang rendah, masa pengeringan yang lama dan pengeringan yang terputus-putus disebabkan oleh cuaca yang tidak dapat diramalkan. Oleh itu, objektif penyelidikan ini adalah untuk membina sistem pengeringan solar dengan prestasi terma yang optima. Dengan kelebihan profil iklim Malaysia serta parameter yang dicadangkan dari kebanyakan kajian, sebuah pengering suria tidak langsung bergabungan dengan pengumpul suria tiga laluan dan unit penyimpan haba telah direka dan dibina. Prestasi terma pengumpul suria tiga laluan telah dikaji dan dioptimumkan dari segi susunan bahan berliang, jenis bahan penyimpan haba dan mod peredaran udara. Pengumpul suria tersebut mencapai kecekapan maksimum setinggi 84.7% ± 9.0% dengan simen dan besi sebagai bahan penyimpan haba, susunan bahan berliang yang longgar dan pengedaran udara paksaan dengan kadar aliran jisim 0.01252 kg/s. Pengering suria diuji dengan kadar aliran jisim 0.00834 kg/s, 0.01252 kg/s dan 0.01669 kg/s, dan suhu ruang pengeringan tertinggi yang dicapai ialah 53.5°C, 65.2°C dan 56.3°C, masing-masing. Daun teh dikeringkan dengan pengering suria dan kaedah pengeringan terbuka pada hari eksperimen yang

sama. Pada hari eksperimen, ketika pancaran cahaya semakin berkurang menjelang lewat petang, bahan penyimpanan haba telah memerangkap haba dan elakkan kehilangan haba dengan cepat. Dalam kaedah pengering suria, daun teh dikering dari jisim 2kg, 66.5%MC_{wb} sehingga 1.123kg, 5.2%MC_{wb}, manakala dalam pengeringan terbuka, daun teh dikering dari jisim 2kg, 66.5%MC_{wb} sehingga 1.191kg, 5.5%MC_{wb}. Kecekapan untuk pengering suria dan pengeringan terbuka adalah 11.27% ± 0.04% and 8.17% ± 0.03%, masing-masing. Kedua-dua kaedah mencapai kandungan lembapan yang dikehendaki dalam masa pengeringan 8 jam. Standard Plate Count dari daun teh yang dikering dengan kaedah pengeringan terbuka lebih tinggi daripada daun teh yang dikeringkan dengan pengering suria, dan kulat dikesan dalam sampel daun teh yang dikering dengan kaedah pengeringan terbuka. Ini menunjukkan bahawa pengering suria dapat mengekalkan suasana pengeringan yang baik dan mengelakkannya daripada pertumbuhan mikroorganisma. Sistem pengeringan suria dalam kajian ini terbukti mempunyai kelebihan dari segi kecekapan pengeringan, kadar pengeringan, penyimpanan haba dan kualiti produk kering.

THERMAL PERFORMANCE OF A TRIPLE-PASS SOLAR DRYER

ABSTRACT

Dehydration of agricultural products is an ancient skill to extend the shelf life of crops and reduce post-harvest losses. Owing to the global food security problem, severe post-harvest losses, disadvantages of open sun drying and environmental issues arised from industrial drying, solar drying technologies has become point of interest of researchers to improve the thermal performances of the solar drying system from different aspect. Existing solar dryer are usually design for specific crops type and facing multiple limitations such as inefficient conversion of solar radiation, low collector temperature, long drying time and intermittent drying caused by unpredictable weather. Hence, the objectives of this research work is to develop a solar drying system with optimized thermal performance. By considering the climatic profile of Malaysia and gathering the recommended parameters from the literature, an indirect solar dryer with triple-pass solar air collector and heat storage unit was designed and fabricated. The thermal performance of the triple-pass solar collector was studied and optimized from the aspect of arrangement of porous media, type of heat storage materials and air circulation mode. The solar collector achieved the maximum instantaneous efficiency of 84.7% ± 9.0% with cement and iron mesh as heat storage materials, loosely packed arrangement of porous media and forced convection of mass flow rate of 0.01252 kg/s. The solar dryer was tested with mass flow rate of 0.00834 kg/s, 0.01252 kg/s and 0.01669 kg/s, and the highest drying chamber temperature achieved were 53.5°C, 65.2°C and 56.3°C, respectively. Tea leaves were dried by using the solar dryer and open sun drying methods on a same experiment day. During the experiment day, when the irradiance began to decrease near late afternoon, the presence of heat storage

materials has retained heat and prevent the collector from rapid heat loss. The tea leaves was dried from 2kg, 66.5% MC_{wb} to 1.123 kg, 5.2% MC_{wb} using solar dryer, whereas from initial weight of 2kg, 66.5% MC_{wb} to 1.191 kg, 5.5% MC_{wb} using open sun drying. The drying efficiency for solar dryer and open sun methods were 11.27% ± 0.04% and 8.17% ± 0.03%, respectively. Both methods have achieved the desired moisture content within 8h drying time. The Standard Plate Count of open sun dried tea leaves was higher than that of solar dried leaves and moulds were detected in the sample of open sun dried tea leaves. This indicates that solar drying methods was able to maintain a good drying environment and prevent the microorganism growth. The solar drying system fabricated in this study was proven to perform better in terms of drying efficiency, drying rate, heat retention and quality of dried products.

CHAPTER 1

INTRODUCTION

1.1 Background

Drying is one of the primitive methods used by mankind in food preservation. Dehydration of fish, meat and crop under the sun or by natural air have been practiced by human since prehistoric times and it has developed into a significant operation in agricultural and food industry. The history of food drying can be found as early as 20,000 BC. There is evidence showing that Middle East and oriental cultures actively dried food in the hot sun since 12,000 BC (Hayashi, 1989). Food with low moisture content is stable, having longer shelf life, easy to store and easy to use in food processing operation. Drying of food products could reduce the packaging size, storage space and transportation cost as well.

Natural sun drying is simple to perform, almost zero cost of operation and can be carried out at any places that are well exposed to sunlight. However, this method has a number of downsides and limitations. Since it is using natural source of energy, the food drying process becomes highly dependant on climatic conditions and is easily affected by ambient conditions such as humidity level, temperature, rainfall, wind speed and cloud cover. In addition, the quality of final products might be unsatisfactory due to the high possibility of contamination by birds, insects, dusts and any foreign objects from the surroundings.

Solar dryer is a device that utilizes solar energy to dehydrate the objects. It is differentiated from sun drying by the use of equipment setup to collect solar energy from sun radiation for drying purpose. Adoption of solar dryer in food drying would improve the efficency of drying process and the quality of dried products. A typical solar dryer enables the food products to be dried in shorter time, higher temperature and more hygienic environment. The first known drying configuration has been discovered in South of France around 8,000 BC. It was made up of a stone paved surface, combined the natural moderate wind velocities and solar radiation to accelerate the drying of crops (Kalogirou, 2014). Between 7,000 and 3,000 BC, there are various solar drying installations have been found around the world, utilizing solar radiation and natural air circulation in food drying. Later on, the industry has started to use biomass, woods and furnace for conventional drying of other substances such as bricks and roof tiles. Over the decades, various types of solar dryer have been designed and developed. For instance, some dryers are designed to dry specific crops type, whereas some of them are integrated with extra energy source and backup system to improve the product yield and shorten the drying time. Despite numerous modern methods have been developed, direct sun drying is still the main choice for rural communities and small farmers, due to limitation on materials, financial and knowledge on solar drying.

1.2 Problem Statement

Climate change, global warming, land degradation and global water crisis have caused significant impacts on agricultural yields and food security. Severe post-harvest loss and the continuous growth of the world population are further threatening the global food security. Agriculture in Malaysia contributes 7% to 9% to the nation's GDP in recent years. It is characterized by dualism, namely, the plantation sector with farm size more than 500 ha and the smallholders sector with farm size less than 2 ha. In fact, smallholders produce about 80% of the food consumed in developing country and contribute significantly to economic well-being of rural communities and food security (IFAD, 2013). As at 2014, 94% of rubber, 96% of cocoa, 45% of oil palm, 97% of fruits and vegetables farms in Malaysia were operated by smallholders (Arshad, 2016). However, smallholders are facing multiple challenges as their productivity, materials, resources and infrastructure are lagging behind the big farms. Solar food dryer is the potential drying technique to assist small scale farmers with limited resources. With some capital investment on solar dryer, they could produce dried products that meet the food standard and quality. There are various type of solar dryer has been studied, but most of them are specially design for certain crops type. Existing solar drying system are facing multiple limitations such as inefficient conversion of solar radiation, low output temperature, long drying time and intermittent drying caused by uncertain weather. Focus of study were concentrated on optimization of single and double pass solar collector. There are many analytical approaches reported that triple-pass able to achieve better performance, however, only limited experimental work are available in literature about it. Hence, this research work would focus to fabricate and optimize a triple-pass solar dryer that able to retain heat during uncertain weather and appropriate for small-scale farms.

1.3 Research Objectives

This research project is undertaken to fabricate and develop a solar drying system with optimize thermal performance. The specific objectives are as follow:

A. To improve the thermal performance of solar collector and solar dryer.

B. To investigate the suitable type of heat storage materials to maintain the performance of solar dryer during low solar irradiance, in order to avoid intermittent drying.

C. To compare the performance and quality of tea leaves that dried under open sun and using solar dryer.

1.4 Scope of Research

The study focused on optimizing the thermal performance of the solar collector and solar dryer. Extensive work was carried out to improve the collector oulet temperature, collector efficiency and dryer efficiency by studying from the aspects of solar radiation intensity, mode of convection, heat storage materials and mass flow rate. The solar dryer with the optimal configurations was used for solar drying of tea leaves and results were compared with tea leaves from open sun drying.

1.5 Structure of Thesis

The thesis is comprised of five main chapters. Chapter 1 is the introductory chapter about the background information of drying, problem statement, objectives of the study, scope of research and structure of the thesis. Chapter 2 provides a literature review related to solar radiation, climate of Malaysia, mechanism of drying process, types of solar dryer and different methods to improve the thermal efficiency. Chapter 3 contains the design and details of each component of the newly fabricated triple-pass solar dryer, followed by the procedure of sample preparation and experiment set-up. Chapter 4 consists of the experimental data, analysis for the performance of the solar collector and solar dryer, system performance during solar drying and review of the quality of dried tea leaves. Lastly, the conclusion and suggestions for future work are summarized in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Solar Radiation

The Sun is an primary, pollution-free and infinite source of energy that sustains all the living things, the terrestrial condition and meteorological phenomena on the Earth such as photosynthesis, rainfall, wind and tides. The energy of the Sun is originated by the continuous nuclear fusion process of Hydrogen (H) into Helium (He) atom in the core of the sun. The Sun releases 3.8×10^{23} kW of energy and the energy is radiated in all direction. Of this amount, only a fraction of the energy, approximately 1.7×10^{14} kW is intercepted by the Earth (Goswami & Kreith, 2016). Solar energy travels to the Earth in the form of electromagnetic radiation, mostly with spectral in the visible, near infrared, and near ultraviolet range. In fact, not all solar radiation will reach on the surface of the Earth as about 30% of it is reflected and diffused into space while about 20% of it is absorbed by clouds and particles in the air. However, even if only 10% of total solar radiation is usable, 0.1% of it will be able to power the whole world (Chen, 2011). Compared with the uneven distributed and rapid depletion in fossil fuels, solar energy has becomes one of the most attractive and promising source of renewable energy, owing to its availability over the world and usability for stand-alone systems especially in the rural area and developing country. There are two types of component in global solar radiation, which are direct and diffuse radiation. Direct or beam radiation is the solar radiation travelling in a straight line from the sun, whereas diffuse radiation is the solar radiation that has been scattered and reflected by the particles in the atmosphere.

2.2 Climate of Malaysia

Different regions of the Earth experience different amount of solar radiation. Malaysia is a country located close to the equator, composed of two major parts that divided by South China Sea, namely Peninsular Malaysia and East Malaysia. The country undergo hot and humid weather throughout the year, along with Southwest Monsoon from April to September and Northeast Monsoon from October to March. Generally, the weather is more dry and less rainfall during Southwest Monsoon whereas it is wetter, more rainfall and wind during Northeast Monsoon. Malaysia has high potential in utilizing solar energy as the country is receiving large amount of solar radiation. Figure 2.1 depicts the average of daily total of Global Horizontal Irradiation (GHI) obtained from The World Bank, covering a period of from 1999 to 2015 in Peninsular Malaysia and from 2007 to 2015 in East Malaysia (WorldBank.org, 2018). A case study of Azhari *et al.* reported that Malaysia has average solar radiation of 4.21 kWh/m^2 to 5.56kWh/m^2 per year, average hours of irradiation of between 4 to 8 hours, average ambient temperature of 26°C to 32°C and average relative humidity of 80% to 90% and never drops below 60% (Azhari *et al.*, 2008). Othman *et al.* studied the solar radiation pattern in Malaysia and reported that the frequencies of occurrence are 51.0% cloudy, 16.5% afternoon rain, 15.7% clear day, 13.7% rainy and 2.8% cloudy with occassional solar intensity above the solar constant (Othman *et al.*, 1993).

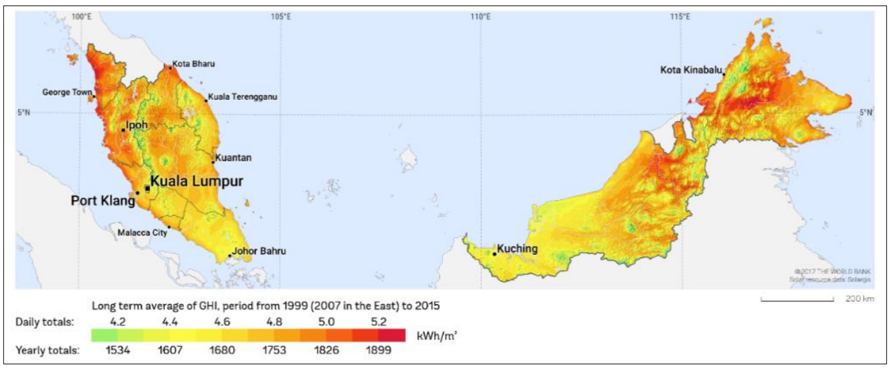

Figure 2.1 Average daily total Global Horizontal Irradiation (GHI) of Malaysia.

2.3 Mechanism of Drying

Drying or dehydration is an energy intensive operation that involves the removal of moisture or water content from an object to a secure level of moisture content that inhibit the deterioration of quality by growth of moulds, enzymic action, and insects attack. Water is the fundamental element of fresh agricultural product and food, and yet its existence might lead to microbial activities, chemical reactions, food spoilage and even the production of toxin (Kerr, 2013). Hence, dehydration becomes one of the widely used method to preserve the food as it removes the water content to reduce the water activity and maintain food stability. The process of thermal drying gives rise to two phenomena that happen simultaneously, which are the transfer of heat from ambient air to surface and internal of the product, and the transfer of mass in the form of moisture from the internal to the surface of the product and evaporation of moisture from surface to ambient. The process goes on until the moisture content is in equilibrium with that of atmospheric air. Equilibrium moisture content is the point at which the vapour pressure on the surface is equivalent to the vapour pressure of the ambient air. Specifically, the moisture desorption from the product is in equilibrium with the moisture absorption from the ambient (Belessiotis & Delyannis, 2011).

The drying process can be described in two behavior period, namely constant rate period and falling rate period. Figure 2.2 shows the typical drying rate curve and moisture content as a function of drying time (Ekechukwu, 1999). During the constant rate period (Zone AB), the surface of the object behaves as free water surface and the unbound moisture is evaporating from the object at a constant rate. The rate of moisture evaporation from the surface is equal to the moisture migration from the internal to the surface. This constant rate period continues until critical moisture content (Point B) is reached. The critical point occurs when the migration of moisture from the interior is less than the moisture evaporation from the surface. After passing through the critical point, the temperature of the object increases, the drying rate decreases linearly and the falling rate period begins. The falling rate period can be divided further into first falling rate period and second falling rate period. Zone BC represents the first falling rate period. During this period, the wet surface area decreases and has less free moisture, therefore, the rate of drying is greatly depends on the internal flow of moisture. The reduction of wet surface to zero is end of the first falling rate period. Zone CD is the second falling rate period in which the surface is completely dry and the plane of evaporation has moved towards the interior of the object. This means that evaporation takes place within the object and the vapour reaches the surface by molecular diffusion and capillary movement through the solid. The amount of moisture removal in this stage is relatively less than that in the constant rate and first falling rate period.

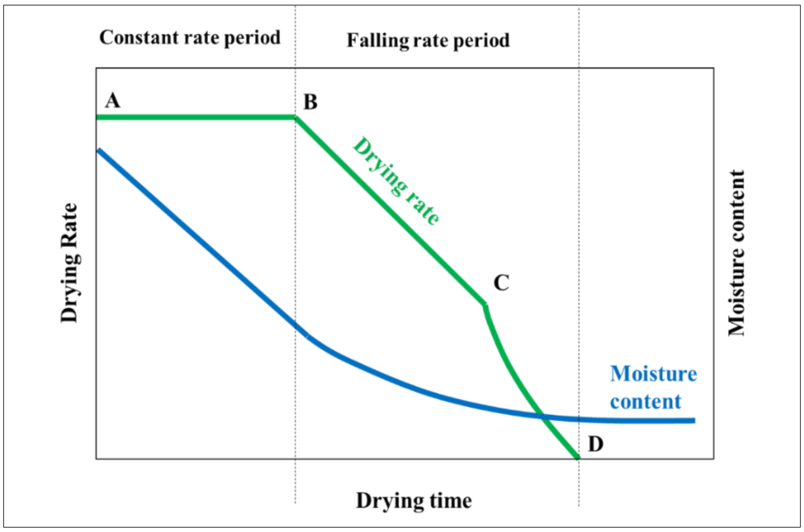

Figure 2.2 Drying rate and moisture content versus drying time (Ekechukwu, 1999)

Open sun drying has been practised by human as food preservation method since prehistoric times throughout the world. The wet crops are spread on an open area and exposed to direct sunlight and natural air circulation. During open sun drying, the absorption of solar radiation and the convective heat transfer from ambient air lead to the increase in temperature of the crops. At the same time, the moisture is migrated from internal to the surface and evaporated to the surrounding. At the early phase, the moisture is evaporated at a higher rate as there is excess moisture on the surface of freshly harvest crop. For the subsequent period, the drying is dependant on the rate of transfer of moisture from the internal to the surface which is subjected to the type and structure of the product (Sodha *et al.*, 1985). Open sun drying is the most accessible method as it can be performed with low cost and without any advanced technology or equipment. However, there is numerous factors that affect the final quality of products from open sun drying and substantial loss of food. As the crops are exposed under open air and direct sunlight, it will be easily contaminated and impacted by the unpredicted weather, animals and insects attack, bacteria and microorganisms infection, and pollutants in the air. Meanwhile, some of the crops are sensitive to direct radiation and high heat. Hence, solar drying has been widely studied and developed in recent decades to utilize solar energy for food drying in a scientific and secure way.

The main purpose of a solar dryer is to provide more heat than that of ambient condition and reduce the relative humidity to create a low equilibrium moisture content atmophere so that the final product can have a relatively low moisture content and thus longer shelf life. For every solar thermal applications, the first step is to convert the solar energy from solar radiation into thermal energy in form of heat. The method of solar drying shall be employed based on the characteristics of the products due to some of the crops require direct sunlight to develop flavor, color and further ripening, while some of the crops are sensitive to direct sunlight and may lead to discoloration, nutrition loss and damage the product (Ekechukwu & Norton, 1999; Sinha *et al.*, 2012). A variety of solar dryer types are reviewed in detail in the following section.

2.4 Types of Solar Dryer

Solar dryer is a type of dehydrator that uses solar energy as the heat source to achieve the desired drying temperature and accelerate the moisture removal from product. Basically, the working principles are similar for all dryer types. The first step is collect and convert the sunlight to heat, then trap the heat by isolating the heated fluid from ambient air, lastly transmit the heat by convection of air to the food for dehydration. There are various types of solar dryer with different mechanism and design, hence it is more convenient to classify them according to the method of heat distribution, namely passive and active solar dryer. Air in passive dryer is circulated naturally by buoyancy force and natural air, while air in active solar dryer is circulated by external ventilator. Both dryer can be further differentiated by method of heat collection which are direct and indirect type dryer. For direct solar drying, solar radiation passes through a transparent cover and directly absorbed by the crops, whereas, for indirect solar drying, solar energy is collected by solar collector and the heated air is circulated to a opaque drying cabinet for drying. Any other solar dryers that incorporate special features and other heating systems such as electrical, biomass or geothermal heater are classified as hybrid dryers. Table 2.1 summarizes the advantages and drawbacks of direct, indirect, passive, active and hybrid features in solar dryer. Figure 2.3 Direct-type passive solar dryer (Islam *et al.*, 2019).Figure 2.3, Figure 2.4 and Figure 2.5 are direct-type, greenhouse type and indirect-type passive solar dryer, respectively. Figure 2.6, Figure 2.7 and Figure 2.8 are direct-type, tunnel type and indirect-type active solar dryer, respectively. Figure 2.9 illustrated different types of hybrid solar dryer.

Table 2.1 Advantages and disadvantages of different solar dryer attributes.

Attributes	Description
Passive type	**Advantages:** - Simpler design, construction and maintenance than active type. - No fuel supplies is needed. - Able to achieve high efficiency if design carefully (performance of solar collector, chimney etc). **Disadvantages:** - Slow overall drying rates due to poor vapour removal. - Highly dependence on convection and radiation. - Less control of drying conditions (temperature, air flow, etc.).
Active type	**Advantages:** - Higher heat transfer rate. - Shorter drying time and thus higher drying rate and product yield compared to passive dryer. - Tends to have higher efficiency since individual components can be designed to optimal performance. **Disadvantages:** - More component to build and higher capital cost than passive type. - Design and operation are more difficult and complex. - Maintenance and operation cost are needed to run the ventilator.
Direct type	**Advantages:** - Simple design, low capital and running cost. - Direct sunshine on product can stimulate further ripening, develop desired color and flavor. - No fuel supplies is needed. **Disadvantages:** - Possibility of over-heat and crop damage. - Highly dependence on weather. - Require large area for mass production (greenhouse type)
Indirect type	**Advantages:** - Suitable for light-sensitive and some perishable crops. - Higher operating temperatures than direct dryers. - Able to achieve greater efficiency if design properly. **Disadvantages:** - Require more capital investment to build solar collector. - Higher running and maintenance cost than direct type. - Difficult to maintain constant conditions within drying chamber due to fluctuation in collector temperature.
Hybrid type	**Advantages:** - Able to operate without sun and avoid intermittent drying by using secondary heater. - Allow better control of drying conditions. - Suitable for large scale drying as drying time is shorten. **Disadvantages:** - Highest capital and running cost among all attributes. - Complicated in terms of design, maintenance and operation. - External energy or fuel supplies are needed to run the secondary heater.

2.4.1 Passive Solar Dryer

Passive solar dryer is known as natural convection solar dryer. Its operation depends solely on the sun radiation without external source and the air circulation is driven naturally by buoyancy force or wind pressure. Passive drying system is used extensively in rural area or small-scale farm due to its low capital and maintenance cost, simple operation step, and most importantly is can be used at remote area with limited access of electricity supply. Compared with traditional drying, passive dryer employs smaller area for same amount of drying capacity, provide protection over the rain, pests and external source of contamination, achieve higher drying temperature thereby shorten the drying time and yield higher amount of product output.

For direct type passive solar dryer, the drying chamber is made with transparent walls so that the sun radiation is transmitted through the walls and fall directly on the crops. In some cases, exposure to direct sunlight helps to stimulate further ripening of greenish fruits, enhance the required color and develop the desired flavor (Ekechukwu & Norton, 1997). The design and construction of direct solar dryer is more simple and economical than indirect type solar dryer of same drying capacity because it does not require additional structures, air-duct or solar collectors. The examples of direct type passive solar dryer are solar cabinet dryer, solar tunnel dryer with chimney, solar tent dryer, solar dome dryer and greenhouse solar dryer. In general, cabinet dryers are single or double-glazed insulated boxes with air inlet at the bottom and air outlet at the upper parts of the cabinet for natural air circulation. Cabinet dryer is suitable for small-scale drying due to the small area of cabinet. Greenhouse dryers are usually built with appropriate vents, position and size to obtain the favorable airflow and reduce heat loss. Greenhouse dryer gives higher controllability on the drying parameters and is more suitable for large-scale drying. Figure 2.3 shown the diagram of three types of natural convection cabinet direct solar dryer chambers developed by Islam *et al.* (Islam *et al.*, 2019). The performance of natural draft chamber was found to be the highest with total moisture removal of 44.5%, 33.3% and 58.9% for thin tube chimney type chamber, attice space type chamber and natural draft chamber respectively. Perea-Moreno *et al.* had carried out a study between open sun drying and the designed solar natural convection greenhouse dryer as Figure 2.4, thereby found that its temperature was 25.20°C higher and relative humidity was 20% less than that of open sun drying (Perea-Moreno *et al.*, 2016).

Indirect type passive solar dryer usually consists of auxiliary components such as solar collector, chimney and drying chamber. For this dryer type, the air is preheated through a solar air heater and the heated air is channeled to drying chamber to carry out dehydration, thus the crops will not undergo direct sunlight. The design and efficiency of solar collector are crucial factors that determine the performance of the dryer as the collector is the only component that receive solar energy. The possible drawbacks of this dryer compared with direct type are higher capital and running cost, more complicated design and require additional attention on the maintenance and operation steps. However, it has greater potential to achieve higher efficiency as those auxiliary components can be designed and developed separately to achieve the most favorable performance. Figure 2.5 is the schematic diagram of an indirect natural convection solar dryer developed by Lingayat *et al.* that composed of a V-corrugated plate solar collector as hot air supply, insulated drying chamber and chimney for exhaust air (Lingayat *et al.*, 2017). For no load conditions, the maximum temperature at the collector outlet and the drying chamber were 81°C and 78°C respectively. 2 kg of banana was dried to 0.5628 kg during the experiment and the dryer was proven more efficient than open sun drying.

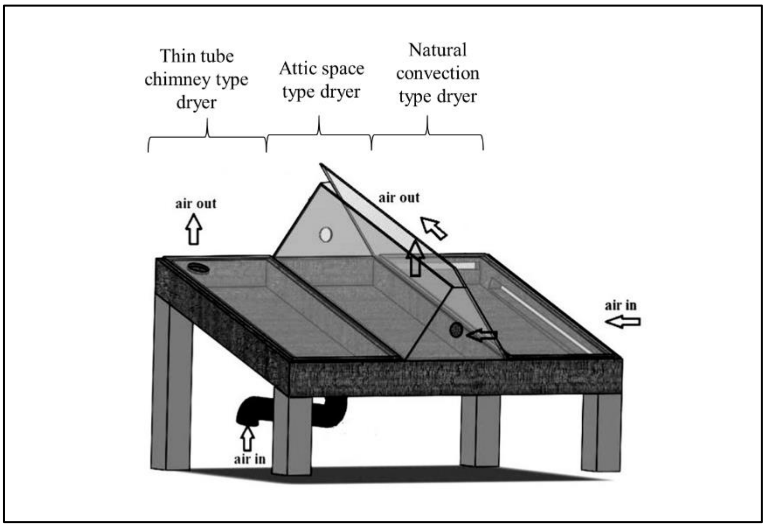

Figure 2.3 Direct-type passive solar dryer (Islam *et al.*, 2019).

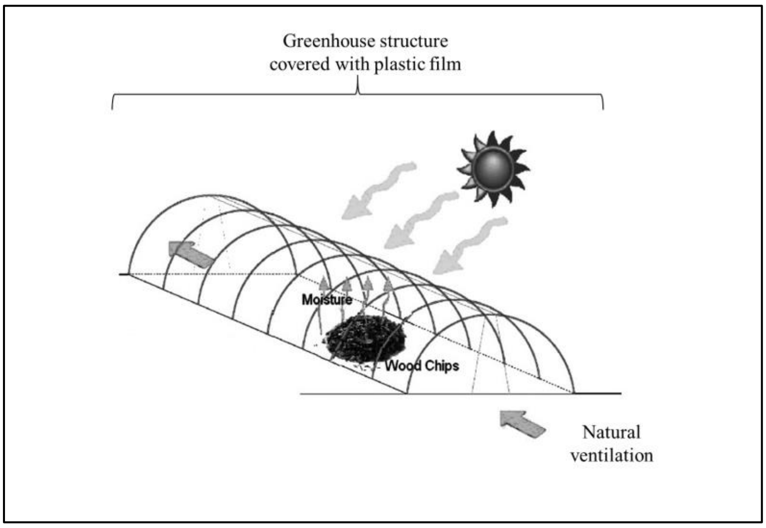

Figure 2.4 Greenhouse type passive solar dryer (Perea-Moreno *et al.*, 2016).

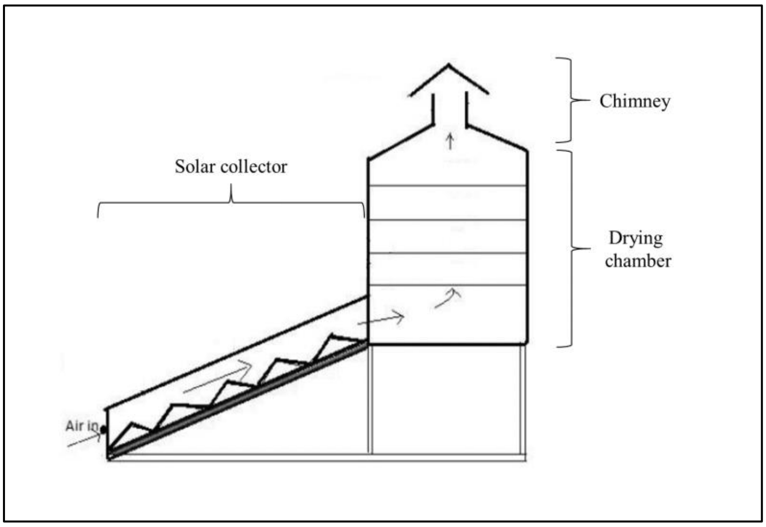

Figure 2.5 Indirect-type passive solar dryer (Lingayat *et al.*, 2017).

2.4.2 Active Solar Dryer

Active solar dryer is mentioned as forced convection solar dryer since its system is integrated with external resources such as fan, blower, pump and ventilator to circulate the air within the dryer. The solar energy from the sun acts as the heat source whereas the external ventilator acts as an accelerator of heated air to transmit from the collector to drying chamber. Active solar dryers can be categorized into direct and indirect type as well.

Direct active solar dryer has similar operating concept and design as direct passive solar dryer in which the crops receive direct solar radiation and no extra heat collector is required, but with additional ventilator to ensure continuous flow of air thereby continuous flow of solar energy. Examples of direct type active solar dryer are forced ventilation tunnel dryer, transparent roof solar barn and solar collector wall dryer. Figure 2.6 is a forced air cabinet solar dryer evaluated by Khater for drying of cucumber seeds (Khater, 2016). The drying temperature was varied between 39°C to 50°C and the average thermal efficiency was 46.64%. Chowdhury *et al.* tested a solar tunnel dryer as shown in Figure 2.7 for drying of jackfruit leather (Chowdhury *et al.*, 2011). The dryer was made up of a transparent plastic covered flat plate collector, two DC fans operated by solar module and raised platform. The sample was dried from an initial moisture content of about 76% (w.b.) to 11.88% moisture content (w.b.) in the solar tunnel dryer within 2 days of drying.

An indirect active solar dryer has four fundamental components which are solar collector, drying chamber, ventilator and air duct. Its initial and operation cost is the highest since it has more components to build and needs electrical energy to run the blower during dehydration process. The parameters such as air flow rate, drying temperature, tilt angle, pressure drop, and performance of solar collector need to take into careful consideration as minor changes may lead to major effect on the overall performance of the dryer. An indirect mode forced convection solar dryer with double pass v-corrugated plate solar collector, drying chamber and blower as in Figure 2.8 was tested with drying experiment of thymus and mint (El-Sebaii & Shalaby, 2013). Thymus took 34 hours and mint took 5 hours to achieve a final moisture content of 11.0% ± 0.5%. The drying cost of thymus and mint in this solar dryer were calculated as 0.087 euro/kg and 0.025 euro/kg, respectively.

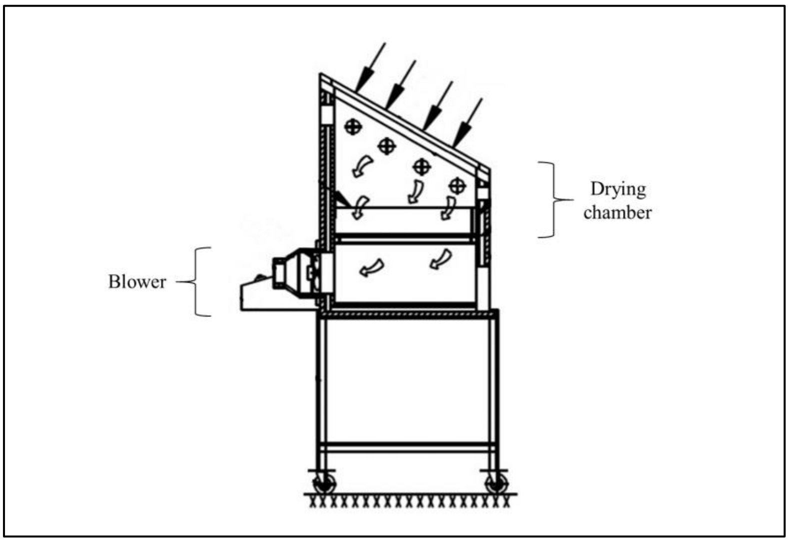

Figure 2.6 Direct-type active solar dryer (Khater, 2016).

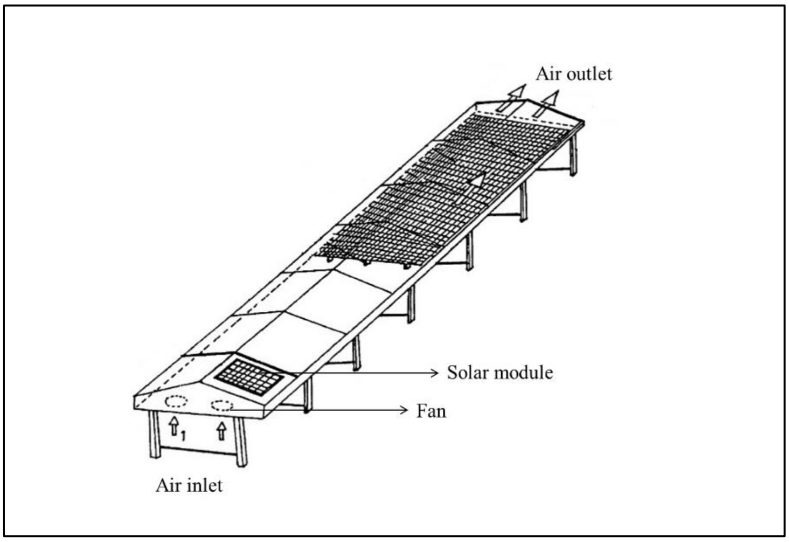

Figure 2.7 Tunnel type active solar dryer (Chowdhury *et al.*, 2011).

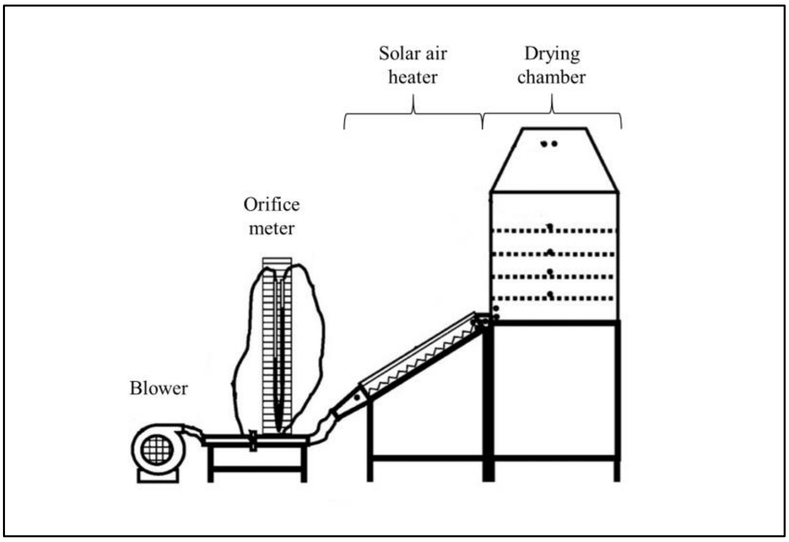

Figure 2.8 Indirect-type active solar dryer (El-Sebaii & Shalaby, 2013).

2.4.3 Hybrid Solar Dryer

Hybrid type solar dryer is a solar drying system that combined with other heating systems or auxiliary unit such as electrical or fossil fuel heater, heat storage and desiccant beds to acquire better control on the drying parameter, diminish the effect of unpredictable weather and fulfill the large-scale commercial drying demands. Tarigan *et al.* had studied an indirect solar dryer with back-up biomass burner and thermal storage as illustrated in Figure 2.9A (Tarigan *et al.*, 2018). The main components were solar collector, drying chamber with chimney and biomass burner with thermal storage. The dryer can be operated in three modes, namely solar energy mode, back-up heater mode and combination of solar energy and back-up heater mode. The dryer obtained an average drying chamber temperature of 56°C and it is suitable for the drying of agricultural products. Slimani *et al.* presented an indirect solar dryer with double pass solar hybrid photovoltaic/thermal collector as shown in Figure 2.9B (Slimani *et al.*, 2016). The PV/T collector consists of monocrystalline photovoltaic module, aluminum metal plate and glazing. First, the air entered the channel formed by the PV module and the metal plate then entered the channel between PV module and glazing. The temperature of the air increases as it passed through the collector due to heat absorbed from PV module and metal plate. The electrical, thermal and overall energy efficiencies obtained were 10.5%, 70.0% and 90.0% respectively, with mass flow rate of 0.0155 kg/s. Figure 2.9C is a direct solar dryer with integration of geothermal water heat exchanger developed by Sandali *et al.* (Sandali *et al.*, 2019). The heat exchanger generated heat from the circulated hot water and became a permanent source of heat. The highest drying air temperature in the solar dryer without using the heat exchanger was 41°C. With integration of heat exchanger inside solar dryer, the maximum and minimum drying air temperature obtained was 58°C and 46°C, respectively. The drying air temperature was able to remain at an average value of 46°C after sunset and throughout the night. A natural convection solar dryer with electrical backup heater was designed and investigated by Sekyere *et al.* and the schematic diagram is illustrated in Figure 2.9D (Sekyere *et al.*, 2016). Solar energy was the main source of heating for the dryer while electrical energy used as back up source during low insolation time. The dryer was tested in 4 conditions which were (i) continuous drying using solar energy during daytime and back up heater during night time; (ii) drying with heat solely provided by back up heater; (iii) hybrid drying during the day; and (iv) use of only solar energy for drying. The average moisture pickup efficiency were 27%, 24%, 11%, and 32% for Condition (i), (ii), (iii), and (iv), respectively, whereas Condition (iv) was slowest in drying and Condition (iii) was the fastest. Eltawil *et al.* had studied a solar-wind ventilation cabinet dryer as shown in Figure 2.9E for drying of medicinal and horticultural plants (Eltawil *et al.*, 2012). The dryer was composed of drying chamber, glass cover, trays and a chimney with a suction axial fan that can spin smoothly by wind power thereby intensify the outlet air flow rate. The dryer achieved temperature between 59.9°C to 72.5°C at no load and the highest temperature achieved at 60° tilt angle with sun tracking. The pretreated potato slices and peppermints reached the desired moisture content in 7-9 hours and 6 hours respectively. Dina *et al.* had evaluated a solar dryer integrated with desiccant as shown in Figure 2.9F for drying of cocoa beans (Dina *et al.*, 2015). The dryer was operated in two modes, namely daytime mode for solar drying and regeneration of desiccant, and nighttime mode for desiccant drying. The drying chamber temperature varied from 40°C to 54°C which was suitable for drying of cocoa beans. Compared with drying time of 55 hours by using direct sun drying, the drying time of solar dryer with adsorbent type desiccant (molecular sieve) and with absorbent type desiccant (CaCl2) were 41 hours and 30 hours, respectively. The use of desiccant has reduced the humidity within the drying chamber and the drying time.

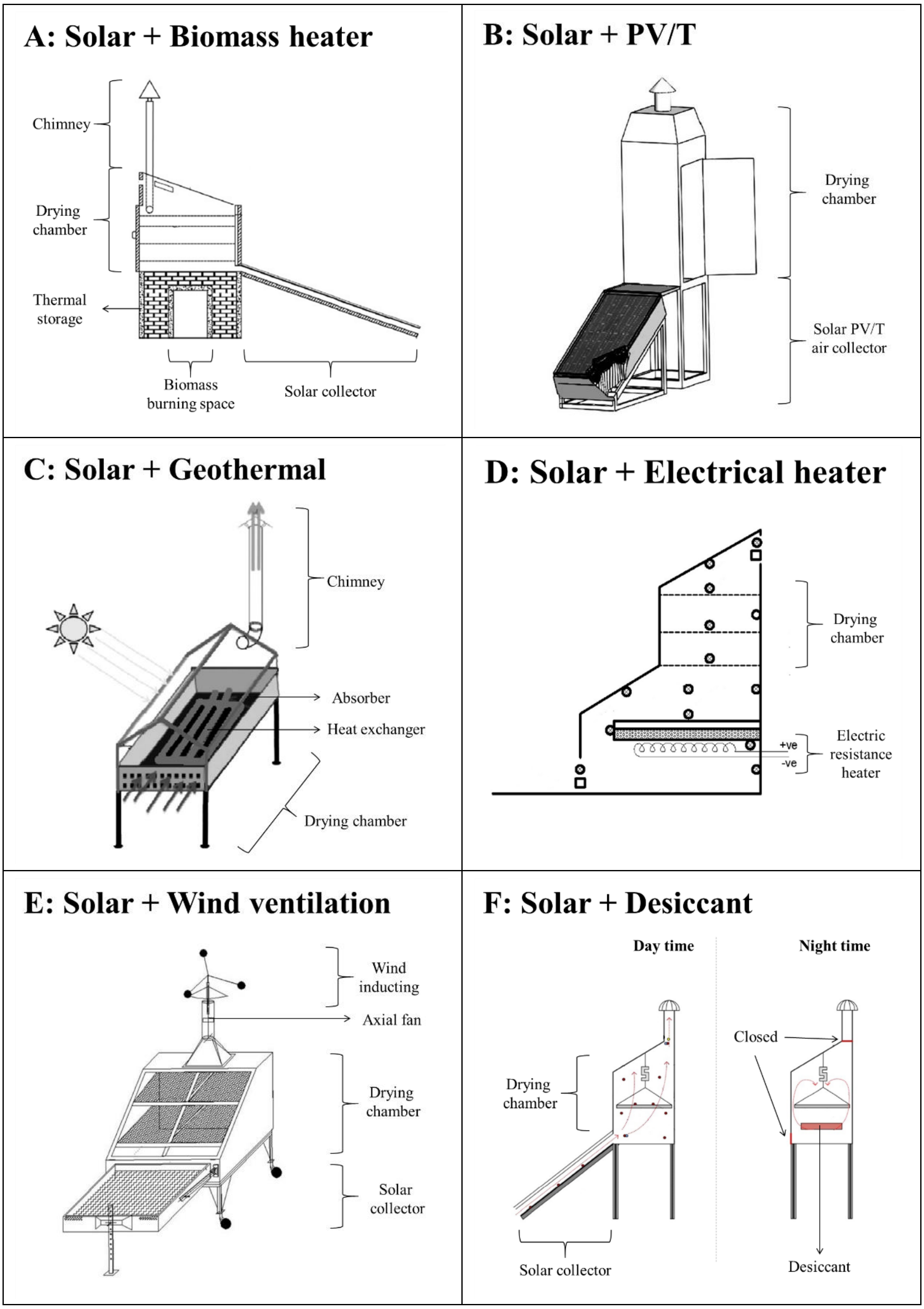

Figure 2.9 Types of hybrid solar dryer (Tarigan *et al.*, 2018; Slimani *et al.*, 2016; Sandali *et al.*, 2019; Sekyere *et al.*, 2016; Eltawil *et al.*, 2012; Dina *et al.*, 2015).

2.5 Improvement of Dryer Efficiency

Solar drying system plays an important role in food drying as it enable people from small farm, rural area and site with limited access of electricity to carry out food dehydration in a better, cleaner and more secure method as well as reduction in fossil fuel and electricity usage. Thus, numerous of studies and research work have been carried out to investigate and improve the thermal efficiency of solar dryer so that the drying system can achieve higher thermal performance and extensively used by people. In general, the dryer efficiency is enhanced from the aspect of solar collector, operational parameters as well as integration with auxiliary unit and additional feature.

2.5.1 Solar Collector

Solar air collector is the core component of a solar drying system as it is the primary section that receives solar radiation and converts the solar energy to thermal energy in the form of heat. However, solar air heaters are usually having lower thermal efficiency than solar water heater due to low convective heat transfer between air and absorber plate. Various effort and attempt have been made to improve the temperature rise, reduce the thermal losses, increase the heat transfer area, alter the air flow arrangement, create turbulence and optimize the collector configurations in order to balance out the low value of heat transfer coefficient.

Absorber plate is the point of interest in the effort to improve the performance of solar collector. Modifications such as utilization of artificial roughness (fins, baffles, ribs), change on the dimension of absorber plate (wave-shaped, V-grooved, finned plate), apply coating materials and use of packed bed absorber have been reviewed and investigated. Akpinar *et al.* studied the performance of solar air heater with several obstacle configurations on absorber plate, namely triangular, leaf shaped, rectangular and without obstacle (Akpinar & Koçyiğit, 2010). Experimental results stated that leaf shaped obstacle achieved the highest efficiency while collector without obstacle obtained the lowest efficiency, owing to the existence of obstacles ensure good airflow, create turbulence and reduce dead zones in the collector. Karim and Hawlader investigated the performance of flat plate, finned and v-corrugated air heater a wide extent of operating and design settings, thereby found out that v-corrugated is the most efficient configuration (Karim & Hawlader, 2006).

Furthermore, an appropriate coating materials on the absorber helps to harness solar radiation effectively. Absorber coating can be divided selective and non-selective coating. Basically, selective coating material has high absorptivity, low emissivity and deposited by chemical or electrical processes while non-selective coating has high absorptivity, high emissivity and prepared by wet chemistry. Majid *et al.* conducted an experimental study on the aluminum ans stainless steel absorber performance with and without flat-black coating (Majid *et al.*, 2015). A remarkable improvement had been observed on coated absorber in which the maximum temperature for coated and non-coated aluminum were 67.2°C and 48.3°C whereas for coated and non-coated stainless steel were 63.9°C and 50.1°C. El-Sebaii and Al-Snani investigated the effect of various selective coating materials on absorber plate, found that Nickel-tin (Ni-Sn) exhibited the best performance with instantaneous efficiency of 0.46 and total energy loss decreased by 30% (El-Sebaii & Al-Snani, 2010).

Packed bed aborber is another preferred method to enhance the performance of solar collector as it can provide a huge absorbing surface and act as heat storage bed at the same time. By pile up several layers of porous absorber materials, the heat transfer area are greatly increased, the turbulence of air is augmented and the solar radiation able to penetrate and absorb into a greater depth through the voids between the absorber bed. A literature review by Rajarajeswari and Sreekumar on matrix solar air heater disclosed that the thermal efficiency of packed bed collector is usually higher than conventional plane solar heater and double pass packed bed collector had better performance than that of single pass collector (Rajarajeswari & Sreekumar, 2016). The volumetric heat transfer coefficient of matrix air heater is relatively high due to the turbulence induced in the air flow. In spite of that, the geometerical parameters of the packed bed (porosity, number of layers, depth to bed element size ratio) and operating parameters (mass flow rate, insolation, Reynolds number) are significant factors that have strong influence on the efficiency which should be take into careful consideration in design of matrix solar collector.

Several investigation has been made on the number of air channel of solar collector. Most of the research work were carried out to compare between single and double pass solar air heater, eventually the performance of double-pass collector tends to surpass those of single-pass. The study of Aldabbagh *et al.* on solar air heater with steel wire mesh packing bed shown that the efficiency of double pass is higher than single pass by 34% to 45% under same mass flow rate and the maximum efficiencies achieved by single and double pass heaters are 45.93% and 83.65% respectively for the mass flow rate of 0.038 kg/s (Aldabbagh *et al.*, 2010). Kareem *et al.* had carried out a comparative study on the single and double pass solar collector with porous media and found that the power output of single pass collector was lower than that of double pass (Kareem *et al.*, 2013). The efficiency of single pass did not exceed 52% even with increase of mass flow rate and ambient temperature, whereas double pass able to achieve 70% efficiency with the same increment. This circumstance is due to the thermal loss is greatly reduced in the double pass design and the porous material helped in heat retention. On the other hand, the analysis of Al Mahdi and Al Baharna expressed that there is remarkable improvements on the thermal performance when the number of air pass increases to three and the construction of double pass or a triple pass collector was cheaper than those required for a single pass collector with the equal performance (Al Mahdi & Al Baharna, 1991). The study of Velmurugan and Kalaivanan on the energy and exergy analysis of multi-pass flat plate solar collector revealed that the energy efficiency of triple pass conditions was higher than that of single pass by 6% to 14% and double pass by 3% to 6% (Velmurugan & Kalaivanan, 2015).

Since double pass collector is found to be more efficient than single pass, the air flow direction becomes a point of interest as well. There are three common air flow patterns which are parallel flow, counter flow and recycle air flow. A typical double pass solar collector consists of two air channel in which one channel is formed by top cover and absorber plate while another channel is formed by absorber plate and back plate. Figure 2.10 presented an overview of parallel and counter airflow pattern of double pass collector. In parallel flow configuration, the air is flow in same direction for both air channel whereas in counter-flow configuration, the air flow through one channel first then enter second channel in opposite direction. Ho *et al.* placed an impermeable sheet into a collector to form double parallel air flow channel and the best efficiency obtained when Graetz number, Gz = 100 and the sheet location was at the middle of the collector (Ho *et al.*, 2007). The performances of parallel and counter flow packed bed solar collectors were presented in an experimental study of Dhiman *et al.* (Dhiman *et al.*, 2012). The thermohydraulic efficiency of counter flow configuration was higher than that of parallel flow for mass flow rate, $\dot{m}$ up to 0.03 kg/s and start reduced for $\dot{m} > 0.03$ kg/s while the parallel flow configuration gained higher efficiency at $\dot{m} = 0.03$-0.06 kg/s. Ho *et al.* discovered that there is considerably