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By: MPAGI Kabuubi Leonard

Subject

Experimental study of air circulation in solar drying cabinets: optimization with phase change materials

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Abstract

The purpose of this master's thesis is to present an experimental investigation into the optimization of air circulation within a solar drying cabinet, with a particular focus on enhancing drying performance through the integration of turbulence generators and Phase Change Materials (PCMs). Experimental trials were conducted on a specially developed mixed-mode solar dryer at the Renewable Energy Research Center (CDER-URAER) in Ghardaïa, Algeria. Various configurations were tested, including a baseline, PCM-enhanced, and designs incorporating internal turbulence promoters. Compared to the baseline, the enhanced configurations reduced the drying time. The integration of hydrated calcium chloride as a PCM maintained a higher temperature compared to ambient during night hours. Analysis of drying kinetics revealed a substantial increase in effective moisture diffusivity. Economically, the optimized mixed-mode solar dryer demonstrated a remarkably short payback period and projected an acceptable annual savings, with the potential to nearly double over its 15-year lifespan.

Keywords: Solar Drying, Mixed-Mode Solar Dryer, Air Circulation, Turbulence Promoters, Phase Change Materials, Heat Transfer, Mass Transfer, Drying Kinetics, Economic Analysis,

ملخص

الغرض من رسالة الماجستير هذه هو تقديم تحقيق تجريبي في تحسين دوران الهواء داخل خزانة التجفيف بالطاقة الشمسية، مع التركيز بشكل خاص على تعزيز أداء التجفيف من خلال دمج مولدات الاضطراب ومواد تغيير الطور .(PCMs) أُجريت تجارب تجريبية على مجفف شمسي مختلط الوضع تم تطويره خصيصًا في مركز بحوث الطاقة المتجددة-CDER) (URAERفي غرداية، الجزائر. تم اختبار تكوينات مختلفة، بما في ذلك خط الأساس، وتصميمات معززة باستخدامPCM ، وتصميمات تتضمن معززات الاضطراب الداخلي. بالمقارنة مع خط الأساس، قللت التكوينات المعززة من وقت التجفيف. وحافظ دمج كلوريد الكالسيوم المطفأ المائي باعتباره مذيب الكلور PCM على درجة حرارة أعلى مقارنةً بالبيئة المحيطة خلال ساعات الليل. وكشف تحليل حركية التجفيف عن زيادة كبيرة في انتشار الرطوبة الفعال. ومن الناحية الاقتصادية، أظهر المجفف الشمسي المختلط الوضع الأمثل فترة استرداد قصيرة بشكل ملحوظ وتوقع تحقيق وفورات سنوية مقبولة، مع إمكانية مضاعفتها تقريبًا على مدى عمره الافتراضي البالغ 15 عامًا.

الكلمات المفتاحية: التجفيف الشمسي، المجفف ذو الوضع المختلط، دوران الهواء، مولدات الاضطراب، المواد المتغيرة الطور (PCMs)، انتقال الحرارة، انتقال الكتلة، حركية التجفيف، التحليل الاقتصادي

Résumé

L'objectif de ce mémoire de master est de présenter une étude expérimentale sur l'optimisation de la circulation de l'air dans une armoire de séchage solaire, en mettant l'accent sur l'amélioration des performances de séchage grâce à l'intégration de générateurs de turbulences et de matériaux à changement de phase (MCP). Des essais expérimentaux ont été menés sur un séchoir solaire à mode mixte spécialement conçu au Centre de recherche sur les énergies renouvelables (CDER-URAER) à Ghardaïa, en Algérie. Diverses configurations ont été testées, y compris une configuration de base, une configuration renforcée par le MCP et des configurations intégrant des promoteurs de turbulence internes. Par rapport à la configuration de base, les configurations améliorées ont permis de réduire le temps de séchage. L'intégration de chlorure de calcium hydraté en tant que MCP a permis de maintenir une température plus élevée que la température ambiante pendant les heures de la nuit. L'analyse de la cinétique de séchage a révélé une augmentation substantielle de la diffusivité effective de l'humidité. D'un point de vue économique, le séchoir solaire à mode mixte optimisé a fait preuve d'une période de récupération remarquablement courte et a projeté des économies annuelles acceptables, avec le potentiel de presque doubler au cours de sa durée de vie de 15 ans.

Mots-clés: Séchage Solaire, Séchoir à Mode Mixte, Circulation de l'Air, Promoteurs de Turbulence, Matériaux à Changement de Phase (MCP), Transfert de Chaleur, Transfert de Masse, Cinétique de Séchage, Analyse Économique.

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Nomenclature

Latin letters

- **AC:** Annualized Cost
- **BR:** Ratio of Flow Blockage
- **$CaCl_2$:** Calcium Chloride
- **$CaCl_2 \cdot 6H_2O$:** Hydrated Calcium Chloride Hexahydrate
- **Cac:** Annualized Capital Cost
- **Cbdp:** Selling Price of Branded Dried Product
- **Ccd:** Capital Cost of Dryer
- **Cel:** Cost of Electrical Energy
- **CFD:** Computational Fluid Dynamics
- **Cm:** Maintenance Expenses
- **Cp:** Specific Heat Capacity
- **Cpl:** Specific Heat Capacity of Liquid Material
- **Cps:** Specific Heat Capacity of Solid Material
- **DR:** Drying Rate
- **d.b.:** Dry Basis
- **Deff:** Effective Moisture Diffusivity
- **DWVGs:** Delta – Winglet Vortex Generators
- **EMC:** Equilibrium Moisture Content
- **FPC:** Flat Plate Collector
- **L:** Half-thickness of the sample
- **L-G:** Liquid – Gas
- **MFCSD:** Modified Force Convection Solar Dryer
- **MR:** Moisture Ratio
- **PCM:** Phase Change Material
- **PR:** Relative Winglet Pitches
- **PV:** Photovoltaic
- **R^2:** Coefficient of Determination
- **Re:** Reynolds Number
- **RH:** Relative Humidity
- **RPM:** Revolutions Per Minute
- **RWVG:** Rectangular-Wing Vortex Generator
- **SHS:** Sensible Heat Storage
- **SIMPLE:** Semi-Implicit Method for Pressure-Linked Equations
- **S-L:** Solid – Liquid
- **S-S:** Solid – Solid
- **S-G:** Solid – Gas
- **TCS:** Thermochemical Energy Storage
- **TEF:** Thermal Enhancement Factor
- **TES:** Thermal Energy Storage
- **THPP:** Thermohydraulic Performance Parameter
- **TRs:** Transverse Ribs
- **TTs:** Twisted Tapes
- **UV:** Ultraviolet
- **V-DW:** V-shaped Delta Winglets
- **V-RW:** V-shaped Rectangular Winglets
- **w.b.:** Wet Basis

- **I:** Solar Irradiance (W/m^2)
- **D:** Diameter (m)
- **e:** Roughness Height (m)
- **Gb:** Generation of turbulence kinetic energy due to buoyancy
- **Gk:** Generation of turbulence kinetic energy due to mean velocity gradients
- **k:** Turbulent Kinetic Energy / Slope (from Fick's Law)
- **L:** Half-thickness of the sample (m)
- **m:** Mass (kg) / Mass Flow Rate (kg/s)
- **Mc:** Initial Moisture Content (w.b. %)
- **Me:** Equilibrium Moisture Content (dry basis)
- **Mf:** Final Weight of Product (kg)
- **M_0:** Original Weight of Product (kg)
- **Mdry:** Final Mass of Dried Product (kg)
- **Mt:** Moisture Content at given time (t) (dry basis)
- **Myear:** Total Annual Mass of Dried Product (kg)
- **n:** System Lifespan (years) / Positive integer (for series solution)
- **p:** Pressure (Pa)
- **Pb:** Payback Period (years)
- **P:** Pitch Length (mm)
- **Pl:** Longitudinal Pitch / Relative Longitudinal Length
- **Pt:** Transversal Length
- **Q:** Heat Stored (J)
- **Qi:** Total Heat Input (kJ/s)
- **Qo:** Total Heat Output (kJ/s)
- **t:** Operational Time (hours) / Drying Time (s)
- **u, v, w:** Velocity Components in x, y, z directions (m/s)
- **Wp:** Power Rating of Fan (W)
- **Y:** Twisted Ratio
- **Sa:** Annual Salvage Value (EUR)

Greek Symbols:

- **α:** Thermal Diffusivity / Angle of Attack
- **η_c:** Drying Efficiency (%)
- **μ:** Dynamic Viscosity
- **μ_t:** Turbulent Viscosity
- **ρ:** Density
- **σk, σε:** Turbulent Prandtl numbers for k and ε
- **Δt:** Time Interval (s)
- **Sk, Sε:** Source terms

Subscripts

- ***j*:** Year of Operation
- ***r*:** Escalation Rate
- ***i*:** Interest Rate

General introduction

General introduction

Humanity's enduring need for effective food preservation has driven continuous innovation throughout history [1]. Drying, as one of the oldest and most fundamental preservation techniques, has played a pivotal role in ensuring food security and mitigating substantial post-harvest losses [2].By reducing the moisture content of perishable agricultural products, drying inhibits microbial growth, extends shelf life significantly, and transforms raw materials into stable, transportable forms, thereby minimizing waste and enhancing economic value [3]. While traditional open-sun drying offers a simple and cost-effective solution, its inherent reliance on unpredictable weather patterns, vulnerability to contamination from dust, insects, and rain, and a complete lack of control over critical drying parameters often compromise both product quality and overall efficiency [4].

In response to these pervasive challenges, solar drying systems have emerged as a highly promising and environmentally conscious alternative. These systems effectively leverage the abundant, clean, and renewable energy from the sun to create more controlled and hygienic drying environments compared to traditional methods. Ranging from basic direct and indirect designs to more sophisticated hybrid and mixed-mode configurations, solar dryers aim to achieve accelerated drying rates and superior product quality while simultaneously reducing reliance on conventional fossil fuels[5]. Despite their significant advantages, a persistent challenge in these systems remains the optimization of air circulation within the drying chambers [6]. Non-uniform airflow can lead to uneven drying, a phenomenon known as case hardening and ultimately, reduced overall system efficiency. This limitation particularly impacts regions with high solar insolation, such as Ghardaïa, Algeria, where the full potential of solar drying is often not realized due to these internal inefficiencies [7].

This Master thesis directly addresses these critical operational limitations by focusing on comprehensively enhancing air circulation within a specifically designed mixed solar drying cabinet. The primary objective is to study the effect of internal modifications on heat transfer and analyse the behavior of the airflow and the increase in turbulence. Turbulence generators, exemplified by winglet rods and twisted tapes, are strategically employed to intentionally disrupt the airflow. Concurrently, Phase Change Materials are incorporated. This integration directly mitigates the inherent intermittency of solar energy, thereby prolonging the effective operational time of the dryer [8].

The comprehensive research conducted at CDER-URAER, involved the experimental testing of a mixed-mode solar dryer under a variety of configurations. These experiments were specifically structured to quantitatively assess the improvements in key drying kinetics parameters, including the rate of moisture content reduction, the overall drying rates, and the impact on the effective moisture diffusivity. Complementary numerical simulations were performed using ANSYS Fluent to provide an insight into the fluid dynamics and heat transfer phenomena occurring within the modified drying chamber. Furthermore, a detailed techno-economic analysis was undertaken to thoroughly assess the financial viability and long-term sustainability of the optimized system.

This work is structured into four main chapters:

- Chapter I provides a comprehensive overview of drying principles, including definitions, mechanisms, and influencing factors. It details various drying methods, with a particular focus on solar dryers and their classification. The chapter also introduces the concepts of thermal energy storage and Phase Change Materials, laying the theoretical groundwork for the subsequent chapters.
- Chapter II presents a critical review of existing research related to the enhancement of drying systems. It specifically examines studies on turbulence promoters, the application of Phase Change Materials in solar dryers, and various modifications to drying chambers, identifying current knowledge gaps and setting the stage for the present study's contributions.
- Chapter III outlines the detailed experimental and numerical methodologies employed in this research. It describes the design and instrumentation of the developed mixed-mode solar dryer prototype, the experimental procedures for sample preparation and drying, and the preparation of the Phase Change Material. This chapter also details the mathematical formulations, boundary conditions, and numerical schemes used for the computational fluid dynamics (CFD) simulations.
- Chapter IV presents and interprets the experimental and numerical findings of the study. This chapter includes the validation of the experimental setup, analysis of drying chamber temperatures, the effect of PCM integration, moisture content reduction, drying rates, and effective moisture diffusivity. It also details the numerical simulation results concerning temperature and velocity distributions within the drying chamber. An energy evaluation and economic analysis of the optimized system are also presented.

Chapter I: Fundamentals of drying

I.1. Drying definition

Drying is the process of reducing the moisture content in a product. In the context of food, drying involves the removal or reduction of water to create an environment that inhibits the growth of bacteria and mold [9]. The initial product may be in solid, semi-solid, or liquid form, but the final dried product is always solid. Drying induces various physical and chemical changes in the product, which can be either desirable or undesirable. These changes may include shrinkage, alterations in color, texture, and taste [10].

I.2. Importance of drying

Drying is one of the one of the oldest and most widely used processes in human history. In any industry where moisture control is necessary, drying is essential. The primary importance of drying is the facilitation of food preservation by inhibiting micro-organism growth. This drastically increases the shelf life of perishables with or without refrigeration. Other importances of drying include;

- It converts products into easy-to-handle solid forms
- Reduces weight through shrinkage which saves on transportation and storage costs
- Transforms perishable items into stable forms such as converting liquid milk to powder
- Produces convenient foods like breakfast cereals and dried fruit snacks that are easy to prepare, have good taste and texture, and are ideal for direct consumer use
- Eliminates the seasonal scarcity of food products by making them available year-round, thereby enhancing commercialization opportunities [11].

I.3. Drying Mechanism

In the process of drying, two main mechanisms are involved; the migration of moisture from the interior of the product to its surface (diffusion) and the evaporation of this moisture from the surface to the surrounding environment. To facilitate this, heat is required to enable the diffusion and airflow for the evaporation process through simultaneous heat and mass transfer. For elaboration, there are specific drying principles that need to be defined. These include;

I.3.1. Hygroscopy

This is the ability of a product to gain moisture by absorption or adsorption depending on the ambient conditions surrounding it. This is determined by the pressure differences between the vapour in the product and the vapour of the surrounding air. If the vapour pressure of the interior is greater than the air vapour pressure, there will be moisture transfer from the product to the surrounding air. If the air vapour pressure is higher, adsorption will take place.

I.3.2. Moisture content

This is the quantity of water contained in a product. It is usually expressed as a percentage. Moisture content comes in two forms;

I.3.2.1. Bound moisture: This is the moisture content in the product that has lower vapour pressure than pure water at the product's temperature. When the product is exposed to air with 100% Relative Humidity (RH), maximum bound moisture content is attained.It is usually retained in small capillaries in the solid.

I.3.2.2. Unbound moisture: This is the water in the product that is in excess of the maximum bound moisture. It can be easily removed by evaporation. All non-hygroscopic materials possess only unbound moisture.

I.3.3. Equilibrium moisture content (EMC)

This is the moisture content that is in equilibrium with the surrounding air at a specific relative humidity and temperature. All hygroscopic products lose or gain free moisture until EMC is reached. At this point, no further drying can take place [12].

I.3.4. Drying Rate

This is the amount of water removed from a product per unit time per unit mass of dry product. It is determined by internal factors like moisture content and external factors like humidity, temperature and velocity of the surrounding air. The drying rate curve is usually used to describe the drying process. It shows that for a drying process, there are three phases involved;

I.3.4.1. Constant drying rate period (Phase 1): Here the product's wet surface loses water at a constant rate depending on the external factors like temperature and velocity of the air. The diffusion of the moisture content to the surface is also constant until the critical moisture content is reached and then transition to phase two.

I.3.4.2. First falling rate period (Phase 2): In this phase, the product's moisture content is in critical state and less moisture is moving to the surface. Hence as the wet surface area decreases, evaporation on the surface keeps on reducing as well.

I.3.4.3. Second falling rate (Phase 3): At this stage, the surface of the product is completely dry and the drying rate is determined fully by diffusion inside the product. Drying continues until equilibrium moisture content is attained. Most of the prolonged drying periods of products takes place in this phase.

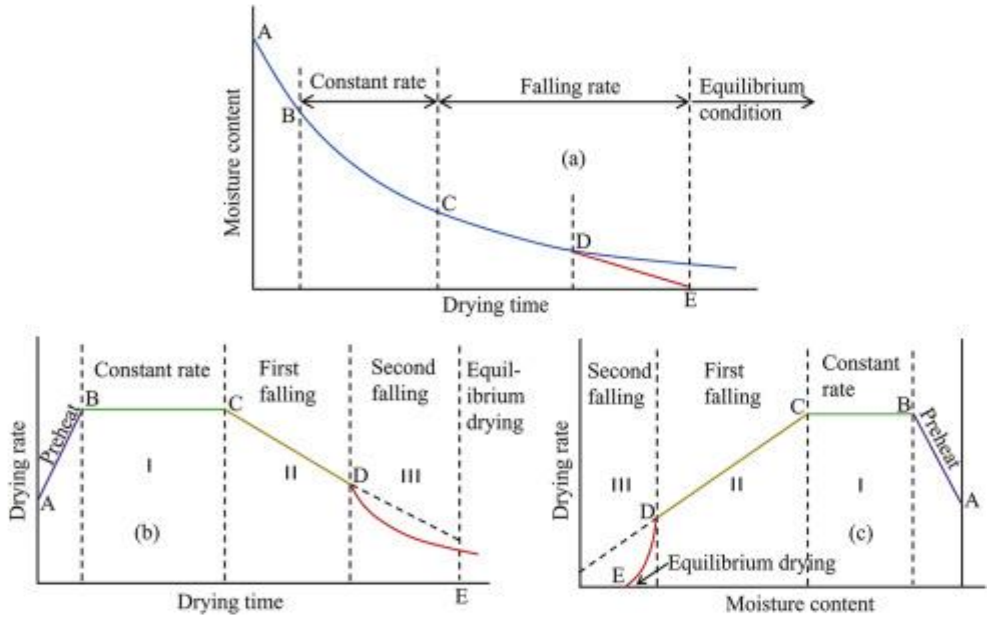

Figure I. 1. Drying phases [13]

I.4. Factors affecting drying

I.4.1. Temperature

In general, the higher the temperature, the higher the heat and mass transfer rate. However optimal drying temperature needs to be obtained for different products. Very high initial temperatures can lead to case hardening. This is a phenomenon where the outer surface of the product dries too quickly and hardens preventing moisture in the interior from moving to the surface for evaporation. Therefore, it is important to maintain a consistent temperature to facilitate uniform drying of the product.

I.4.2. Air velocity

Air is responsible for continuously transferring heat to the product and taking away the saturated water vapour around the product. Therefore, the higher the air velocity, the higher the rate of moisture removal from the product especially in the constant drying rate period which shortens drying times. However, high velocities beyond certain limits can create whirlpools and hotspots which lead to uneven drying.

I.4.3. Humidity

Since the water evaporation rate depends on the partial pressure of water vapour in the air surrounding the product and the partial pressure of water vapour on the surface of the product. Therefore, the lower the relative humidity of the air surrounding the product, the faster is the rate of evaporation of the water from the product. For effective drying, the relative humidity should be below 60%.[14]

I.4.4. Structure and properties of the material

The physical structure, chemical composition, shape and size of the product, the thickness of the product layer and the way of internal moisture binding vary from one product to another. When different products are dried under the same conditions, the drying rate is different for each product.

I.5. Types of drying methods

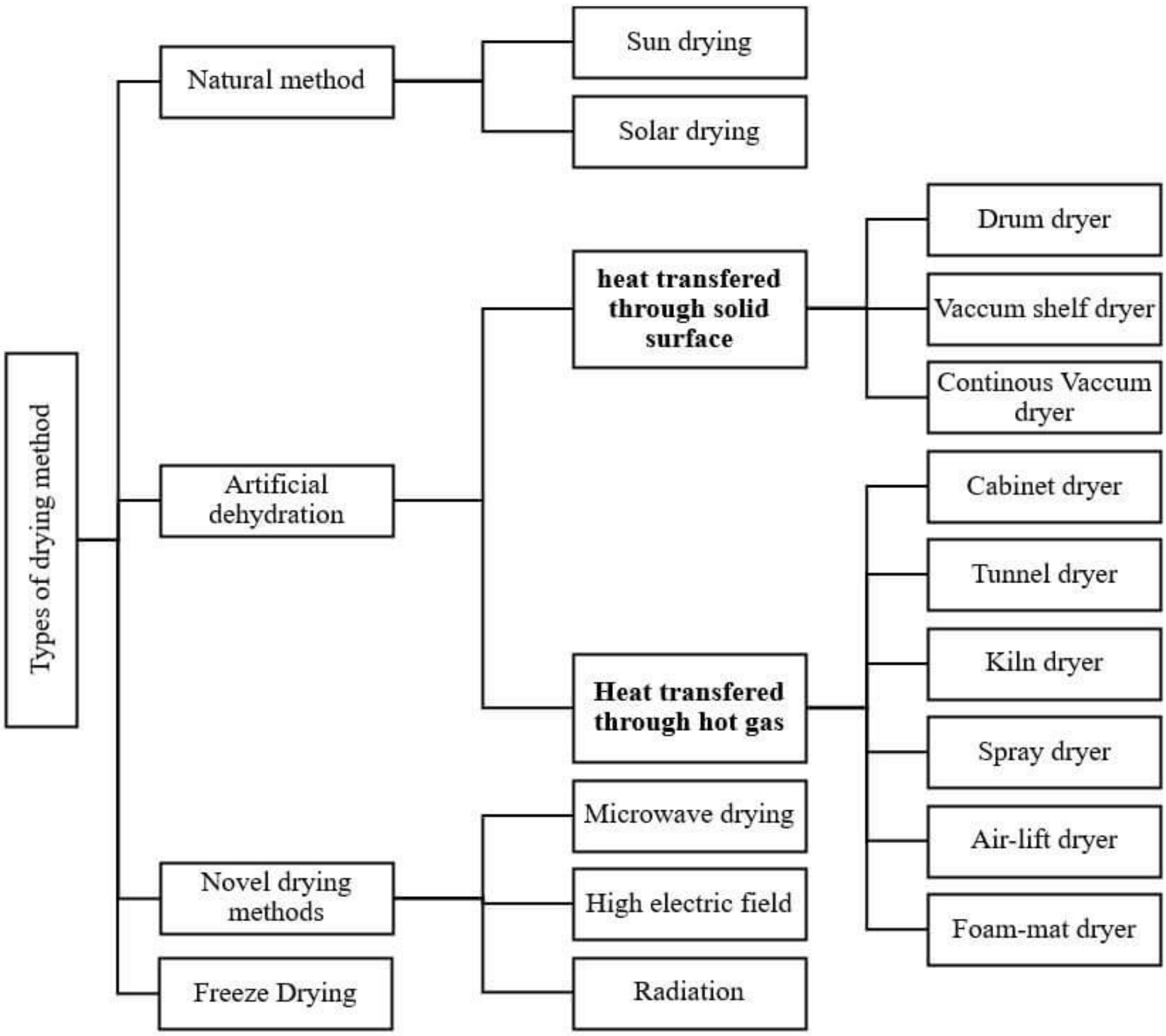

Figure I. 2. Types of drying methods [15]

There are two distinct methods of drying; Natural and artificial drying methods

I.5.1. Natural drying method

I.5.1.1. Open Sun Drying

This is the use of sunlight to dry the products. Open sun drying is considered a traditional method and it has been used throughout mankind’s existence. The food products are exposed to sunlight for long periods in order to lose enough moisture.

It is a very cheap and easy to implement method. However, it depends on the weather conditions which makes it very unreliable. Also, the food products are exposed to insects and birds that may contaminate or eat the product. With the adoption of different types of solar dryers, most of these cons have been eliminated.

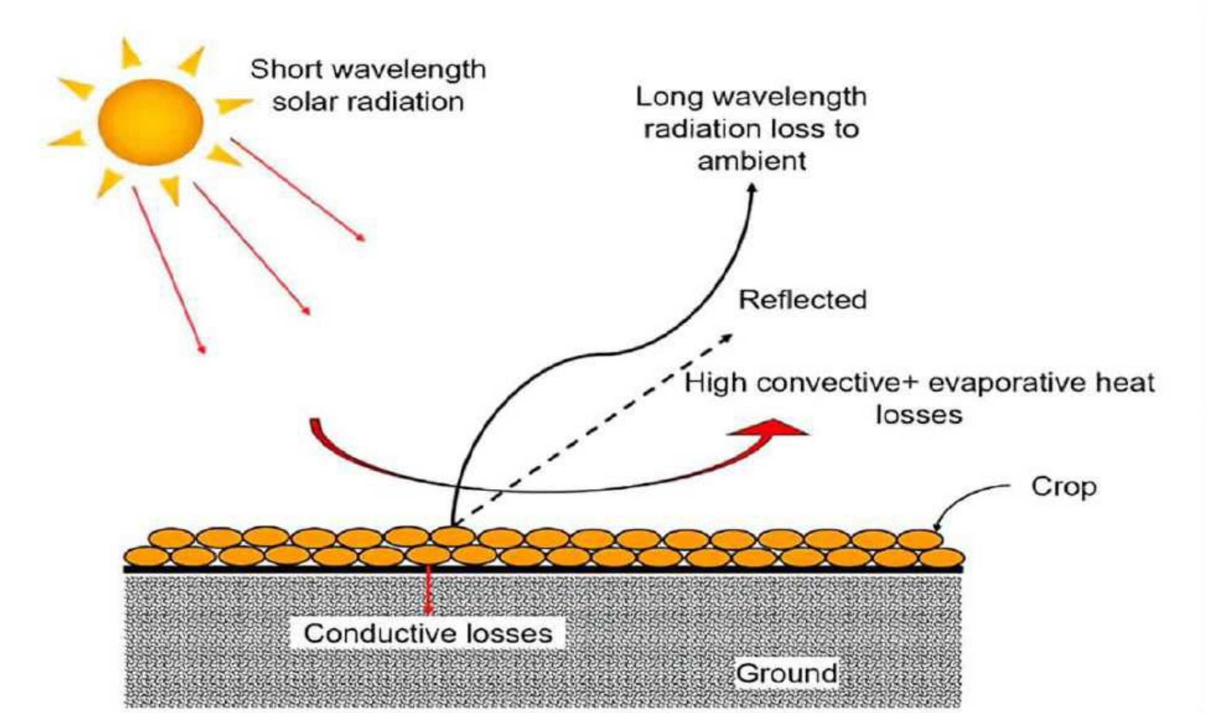

Figure I. 3. Open Sun Drying [16]

I.5.1.2. Shade drying

It is very similar to open sun drying with the only difference being that the product is placed under a shade to protect it from the direct sunlight. It is dependent on full air circulation and therefore cannot be done inside a building but rather an open-sided shade to let in as much air as possible. Shade drying facilitates the retention of the product's quality but it is the slowest drying method [17].

I.5.2. Artificial drying methods

I.5.2.1. Oven/ Convective/ Hot-air drying

It is the use of hot air to transfer heat to the product and effectively remove the moisture. It is commonly used in industries where fast drying rates are required. Unlike solar drying, all the drying factors like air velocity, temperature and humidity are controlled and adjusted depending on the desired product result. However, it consumes a lot of energy and causes shrinkage of the products [18].

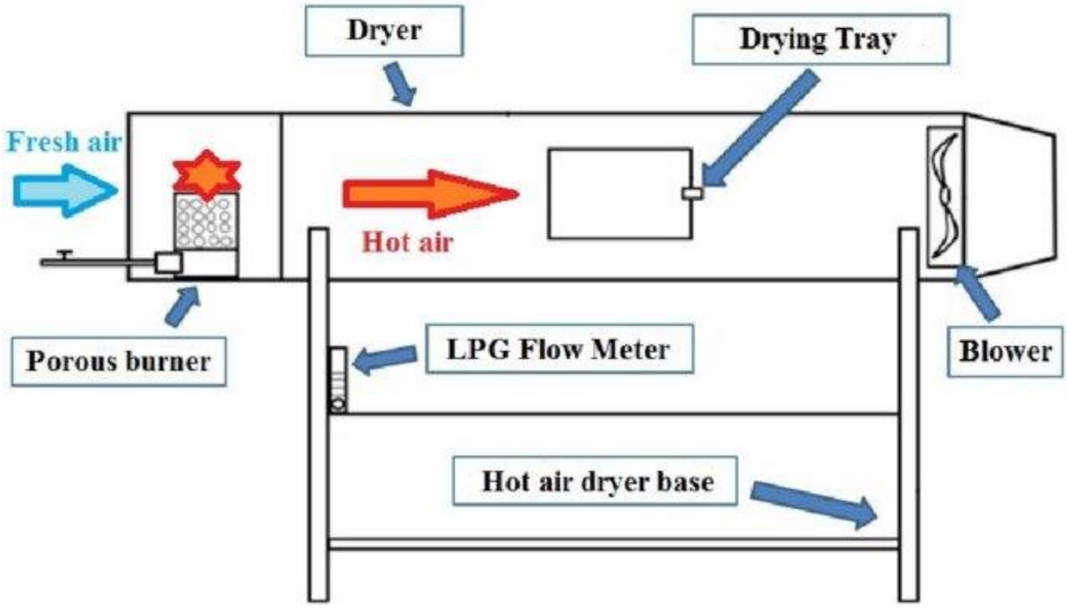

Figure I. 4. Oven Drying [19]

I.5.2.2. Freeze/ lyophilization/ cryodesiccation drying

This is the removal of the moisture content of a product by sublimation at low pressure. The product is first dehydrated through freezing at a low pressure and then the ice is sublimated off. This method differs from other conventional drying methods that depend on heat for water loss. Freeze dried products maintain their flavor, have minimal volume change, structural integrity is maintained and rehydrate very fast and completely. However, it is a very costly method and it is reserved for high high value products like seasonal fruits and vegetables for astronauts and cosmonauts [20].

I.5.2.3. Microwave drying

This is the use of microwaves for drying products. This is possible because water molecules in the product are electric dipoles and try to align when hit by an electric field. This collision generates heat and enables internal moisture removal even in the initial stage of drying unlike other drying methods. It is also the only drying method that doesn't involve the heating medium coming into contact with the product's surface [21].

I.6. Solar Dryers

A solar dryer is a simple device that uses heat from the sun to dry products. It is basically a solar/ air combination. The product is placed in an enclosed drying chamber and heated air is passed over it to dry it. The air is heated by solar radiation which reduces its humidity level and makes it more efficient in enabling the drying process.

I.6.1. Components of solar dryers

A basic solar dryer consists of a solar collector, a drying chamber and an air auxillary system. The solar collector captures solar radiation and transforms it into thermal energy. The drying chamber is an enclosed insulated space where the product is placed. The auxillary system improves the efficiency of the dryer and consists of components such as blowers and fans that facilitate movement of air around the system.

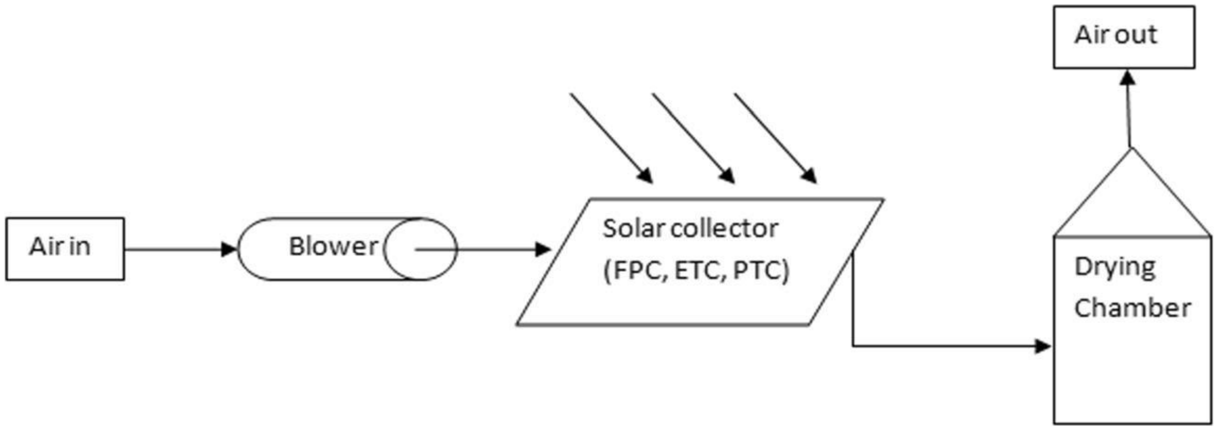

Figure I. 5. Basic components of Solar Dryer [22]

I.6.2. Operation principle of solar dryers

The operation of a solar dryer involves the management of the air flow throughout the system. The thermal energy from the solar collector heats up the incoming air. The hot air is then circulated through the drying chamber absorbing the moisture content of the product. The amount of moisture removed from the product depends on the temperature of the hot air, humidity and its velocity. These parameters need to be precisely controlled to guarantee effective and consistent drying [23].

I.6.3. Solar Collector

A solar collector is a component that captures solar radiation and transforms it into thermal energy. The heat is transferred to the working fluid of the system. In an air based collector, the heated air from the collector is circulated in the drying chamber. In water based collectors, it's still air that does the extraction of moisture from the product. It gets heated up by the hot water directed towards the drying chamber. Air based collectors are the most used because of their ability to absorb both direct and diffuse radiation [24]. There are two distinct types of solar collectors: concentrating and non–concentrating solar collectors. Concentrating solar collectors use an optical device (reflector which needs to be kept clean) to focus solar radiation to a smaller concentration area(receiver). This enables the acquirement of very high temperatures but they require a sun tracking system since they gather very little diffuse radiation.

Non-concentrating solar collectors consist of four main components that include: a transparent cover that allows penetration of short-wave solar radiation and is opaque to long-wave radiation, a solar thermal absorber that's usually painted black since it absorbs all light wavelengths and heat, a collector base and a heat transfer medium. Non- concentrating collectors are usually tilted and oriented according to geographical and meteorological data to ensure maximum solar radiation absorption since they have a low concentration ratio [25].

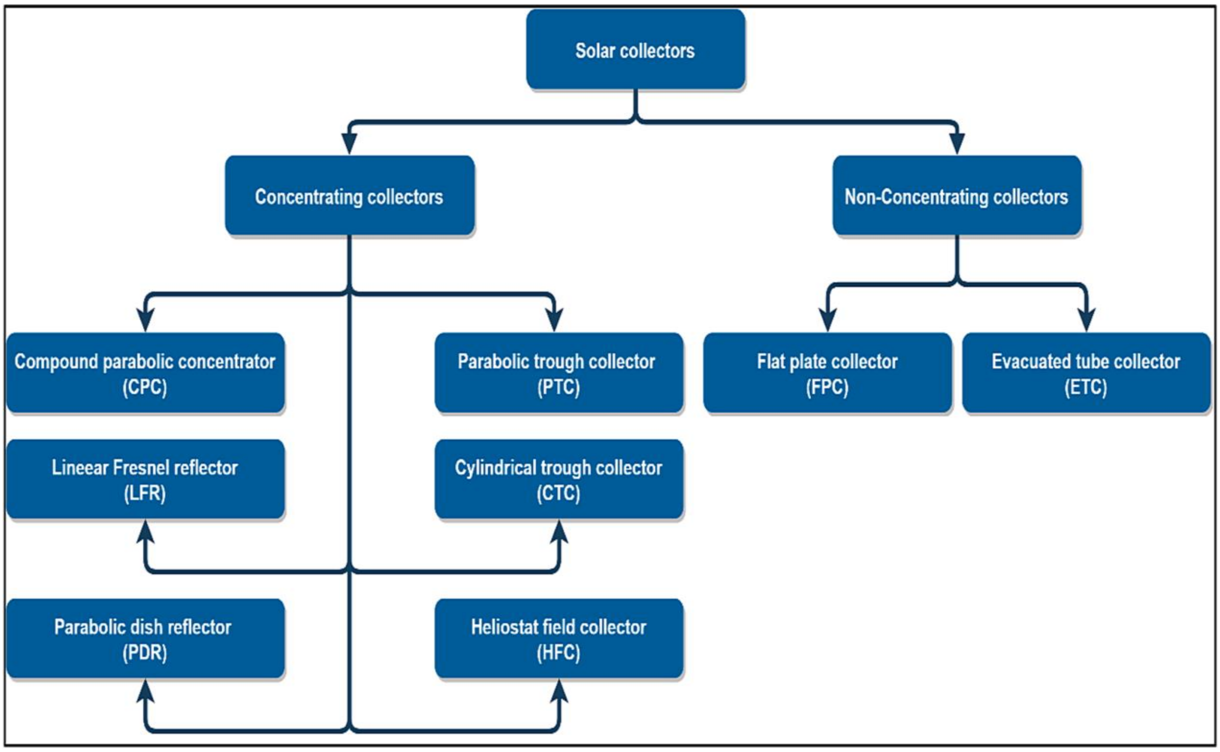

Figure I. 6. Types of Solar Collectors [26]

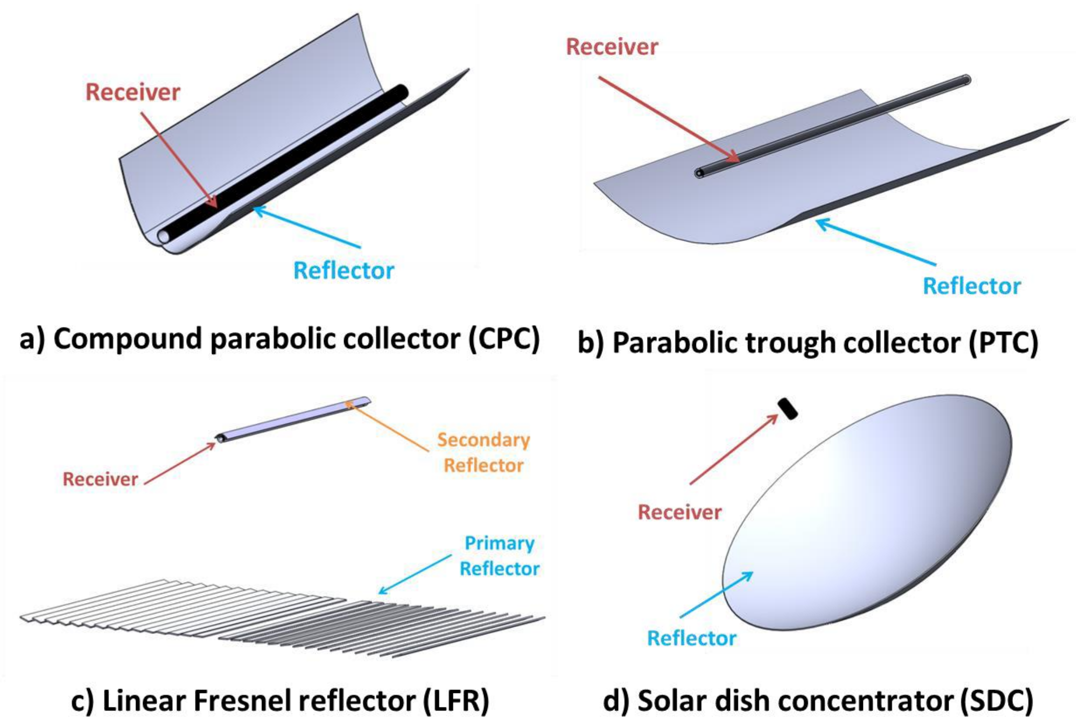

Figure I. 7. Concentrating Solar Collectors [27]

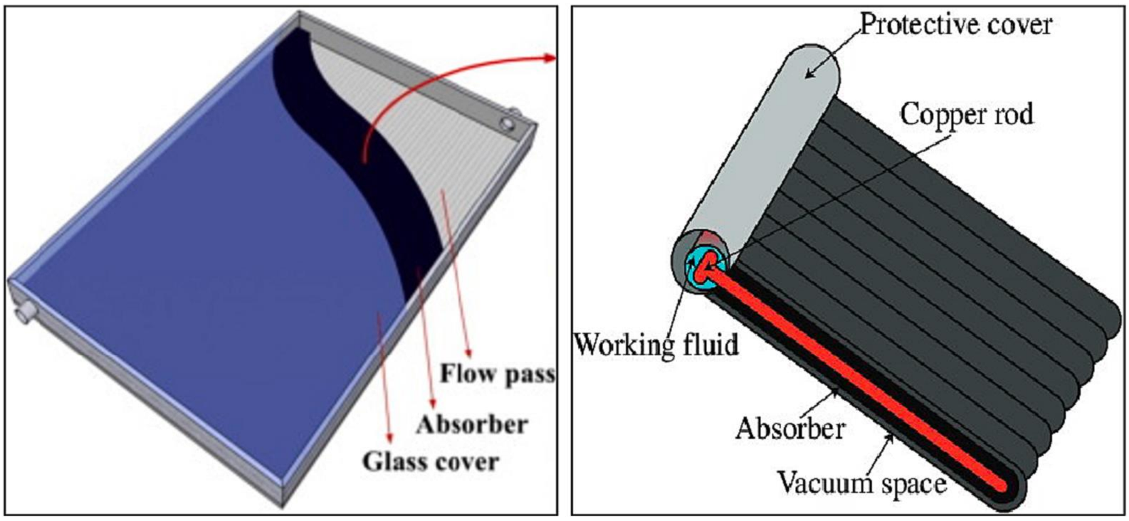

Figure I. 8. Non – concentration solar collectors [26]

I.6.4. Drying Chamber

This is where the product to be dried is placed. The chamber can be combined with the solar collector or the two can be separate. Constructing a drying chamber is not complicated and can be easily done. The structure can be of materials like wood, cement or steel. Insulation can be added to avoid heat loss. The types of chambers are shown in fig below.

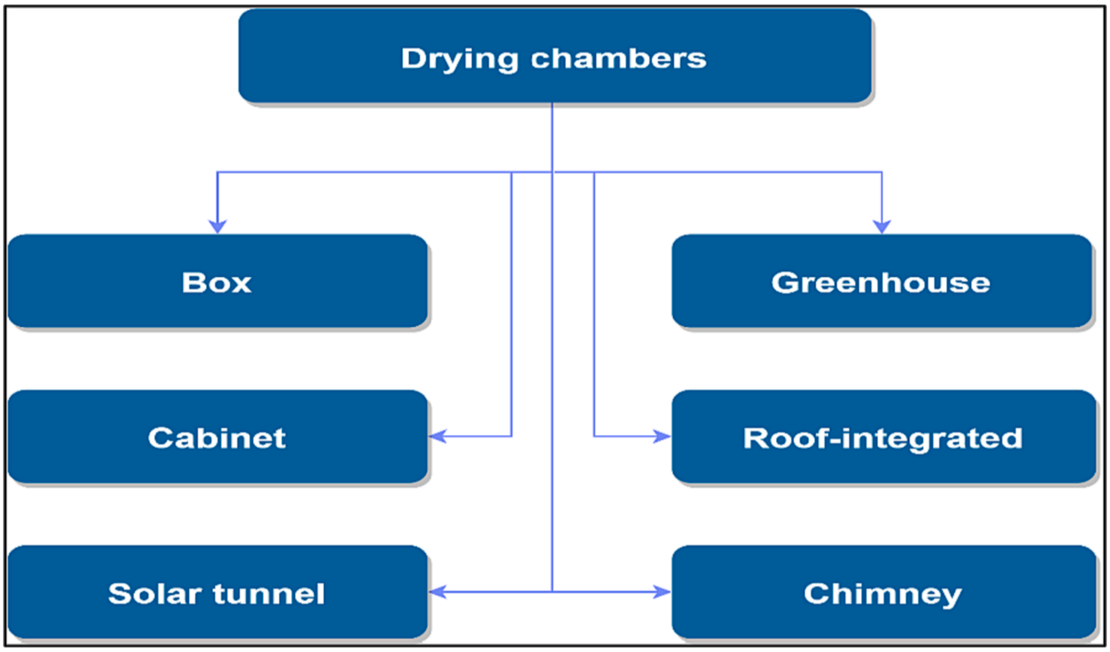

Figure I. 9. Types of Drying Chambers

I.6.5. Auxiliary system

This consists of components that enhance the efficiency of the solar dryer. A typical solar dryer can function without them. They may include a blower and fans as well as supplementary energy sources like thermal energy storage.

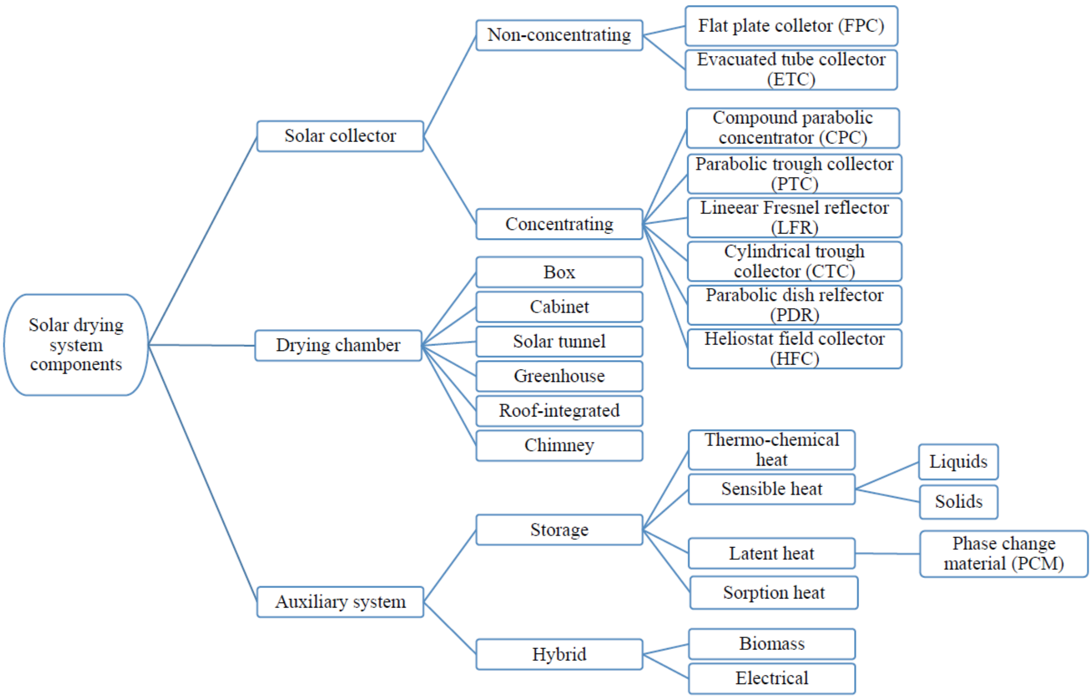

Figure I. 10. Solar Drying system components [25]

I.6.6. Classification of Solar Dryers

With the various disadvantages of open sun drying albeit cheap, solar dryers emerged as a reliable alternative. They are broadly classified based on solar radiation exposure in three types: direct, indirect and mixed. All these three types of dryers can either be passive or active solar dryers. In passive solar dryers, the air circulation for drying occurs naturally or by buoyancy [28]. For active solar dryers, air circulation is forced by the use of fans.

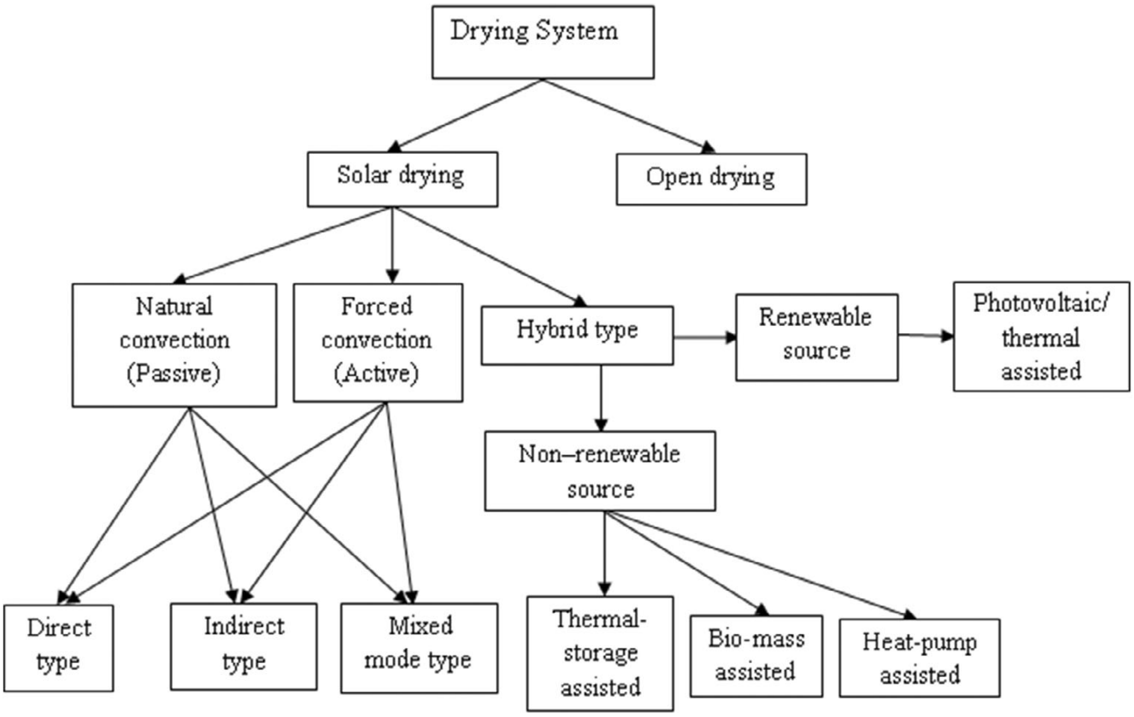

Figure I. 11. Classification of Solar Dryers [29]

I.6.6.1. Direct Solar dryers

These dryers consist of only a drying chamber. The enclosure is transparent and may be made of glass or plastic and acts as the solar collector. The product is directly exposed to the sunlight. When the solar radiation hits the glass cover, some of it gets reflected back to the atmosphere and the other gets transmitted into the chamber. It heats up the circulating air (natural/passive or forced/ active). This leads to an increase in the product temperature and loss of moisture through evaporation [16].

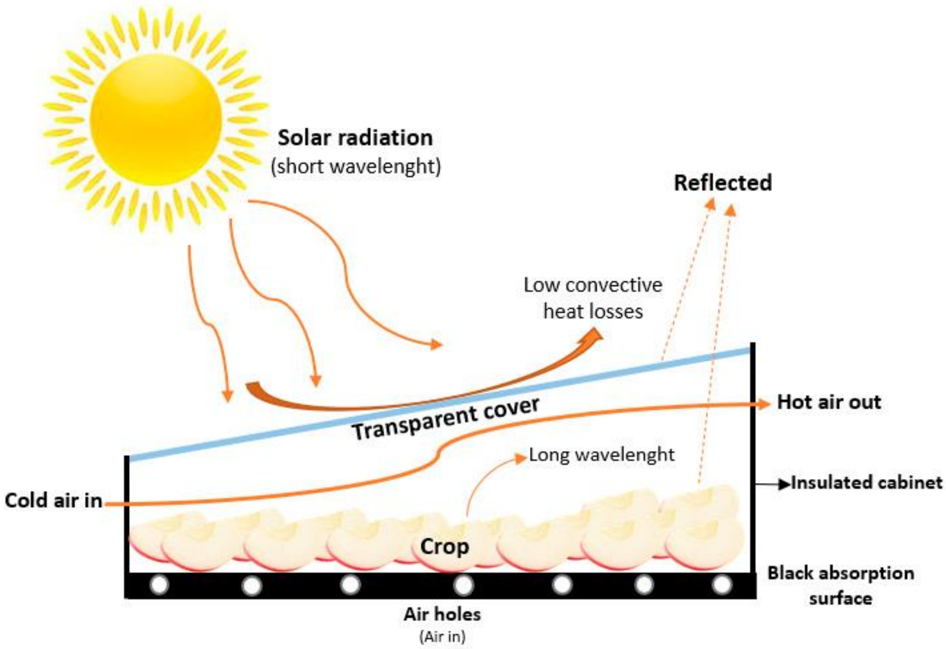

Figure I. 12. Direct Solar Dryer [30]

Table I. 1. Advantages and disadvantages of direct solar dryers

Advantages	Disadvantages
• Least expensive • Simple to set up • Product is protected • Environmentally friendly	• Efficiency is dependent on climatic conditions • Direct exposure to UV radiation leads to discolouration of product • Little control over operating conditions like temperature • Limited to small-scale

I.6.6.2. Indirect Solar dryers

These consist of an opaque drying chamber and an independent solar collector unit. The two units are connected by an insulated conduit. The product is not exposed to the direct sunlight at any one point during the drying process which protects it from UV radiation damage. The solar collector is usually tilted to collect more solar radiation as opposed to when flat. The atmospheric air is heated in the solar collector passively by natural convection or actively using a fan. The air is then conducted into the drying chamber and passed over the moist crops. Evaporation occurs due to the difference in moisture concentration between the heated air and the product's surface (heat and mass transfer on the product's surface). The hot air then leaves the chamber humidified by the dried product's moisture.

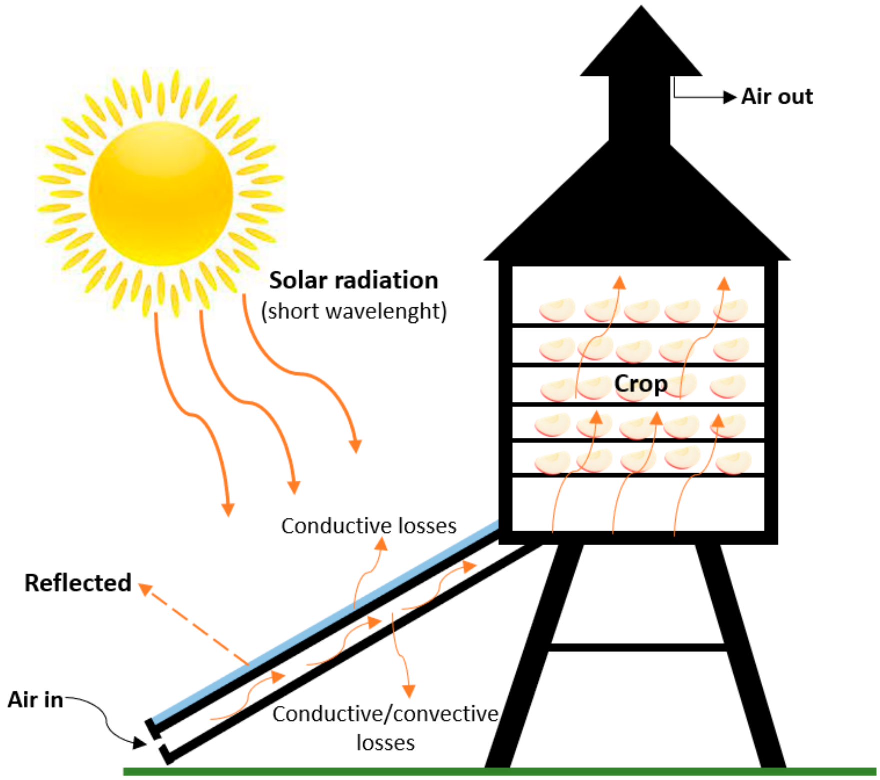

Figure I. 13. Indirect Solar Dryer [30]

Table I. 2. Advantages and disadvantages of indirect solar dryers

Advantages	**Disadvantages**
• No direct exposure to sunlight hence preserving the quality of the product • Better control over drying process	• More expensive to setup than direct solar dryers • Low drying rates especially in passive mode

I.6.6.3. Mixed-mode Solar dryers

As the name suggests, mixed-mode solar dryers are a combination of direct and indirect solar dryers. They are indirect solar dryers with transparent drying chambers to let in solar radiation n as an extra source of heat energy.

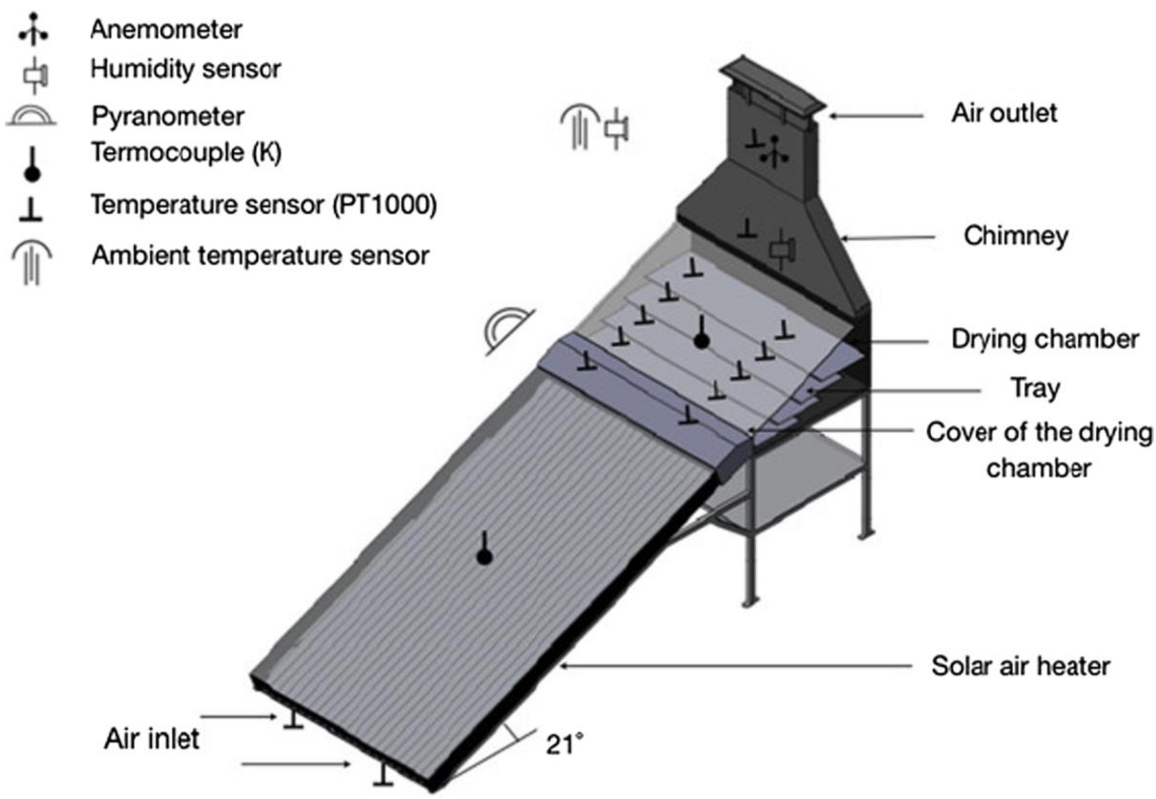

Figure I. 14. Mixed-mode Solar dryer [31]

Table I. 3. Advantages and disadvantages of mixed-mode solar dryers

Advantages	**Disadvantages**
• Accelerated drying process	• Direct exposure to UV radiation leads to discolouration of product • High initial costs involved

I.6.6.4. Hybrid solar dryers

One of the major drawbacks of solar energy is its intermittency and solar dryers are also susceptible to this. Hybrid solar dryers use solar radiation as well as an additional source of energy to assist in the drying process. This source can be biomass, electric or thermal storage. These are known as auxiliary energy sources. The dryer can operate in single or double mode with the extra energy source preheating the air. For fast drying while maintaining good product quality, hybrid solar dryers are considered to be the most capable as they have efficiencies ranging between 17% to 29% [28].

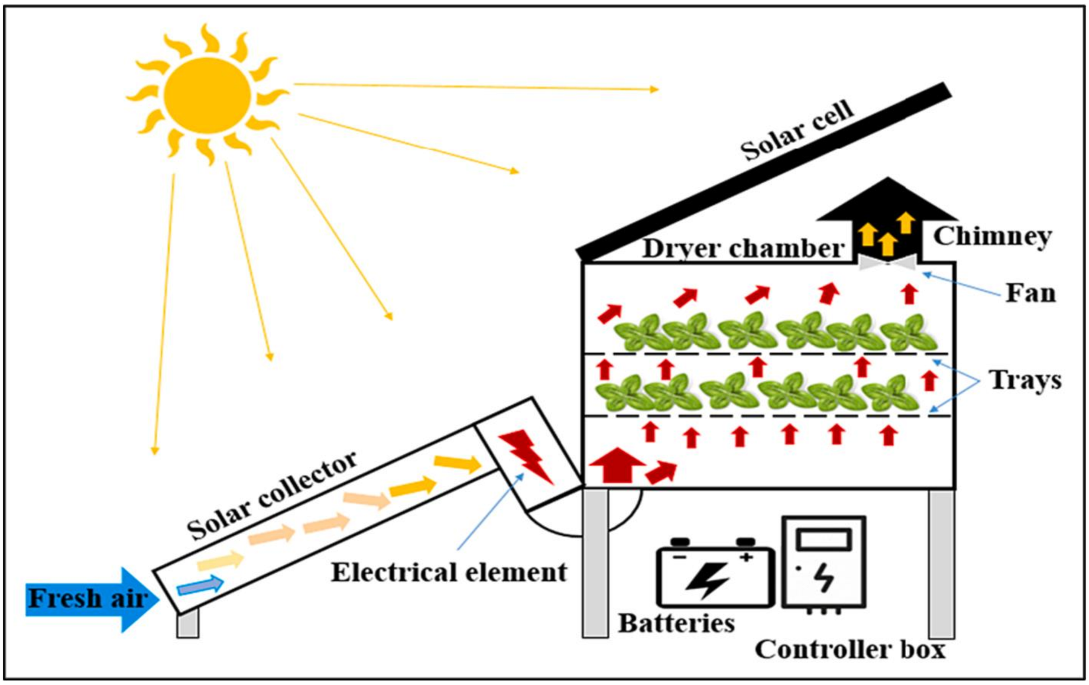

Figure I. 15. Hybrid Solar dryer [32]

Table I. 4. Advantages and disadvantages of hybrid solar dryers

Advantages	Disadvantages
• Continuous and therefore faster drying process • Good product quality • Can be used in any climatic conditions • Large quantity of product can be dried at the same time as the required temperatures can always be obtained	• Very costly to set up • Require complex control systems • They are not environmentally friendly

I.7. Thermal Energy Storage

Thermal energy storage (TES) is technology that enables the collection of heat or cold energy for later use. TES involves three processes: charging, storing, and discharging. There are three main TES categories: sensible, latent and thermochemical heat storage.

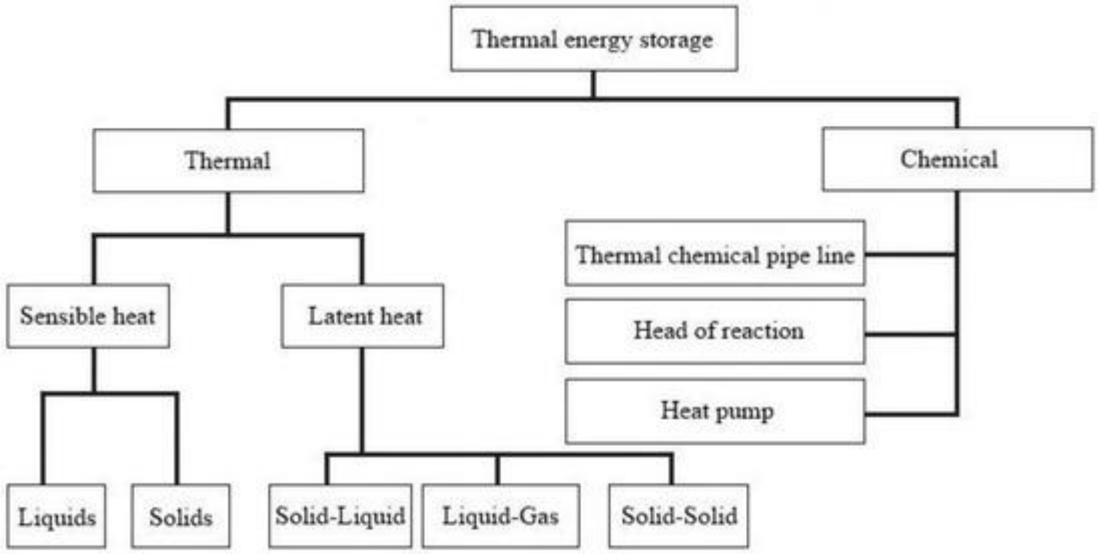

Figure I. 16. Thermal Energy Storage types [33]

I.7.1. Sensible Heat Storage (SHS)

This is the heating of a storage medium to store the heat without change of phase. It is the simplest and commonest mode of TES. The storage medium can be solid like rocks and sand or liquid like water. The amount of heat stored depends on the specific heat capacity, quantity and temperature difference of the storage medium. It is denoted as: [34]

$$Q = mC_p(T_f - T_i) \tag{I.1}$$

Where:

Q = Heat stored (J)

m = mass of the storage medium (kg)

C_p= Specific heat capacity of the medium (J kg^{-1} K^{-1})

T_i= initial temperature (°C)

T_f= final temperature (°C)

Water has a very high specific heat capacity and is readily available hence it is the commonest Sensible Heat Storage medium used.

I.7.2. Thermochemical energy storage

This is the use of thermochemical materials that generate heat by endothermic or exothermic processes. Heat is applied to material C to create two separate portions A and B. The two portions are kept separate until the stored heat is needed. For the discharge process, the two portions are combined under favorable temperature and pressure to release the stored heat [35]. The common working pairs used in TCS systems include:

- Silica gel/water

- Magnesium sulfate/water
- Lithium bromide/water
- Lithium chloride/water
- NaOH/water [36]

TCS has a high energy density and minimal heat losses but is very costly and environmentally unfriendly to produce [37].

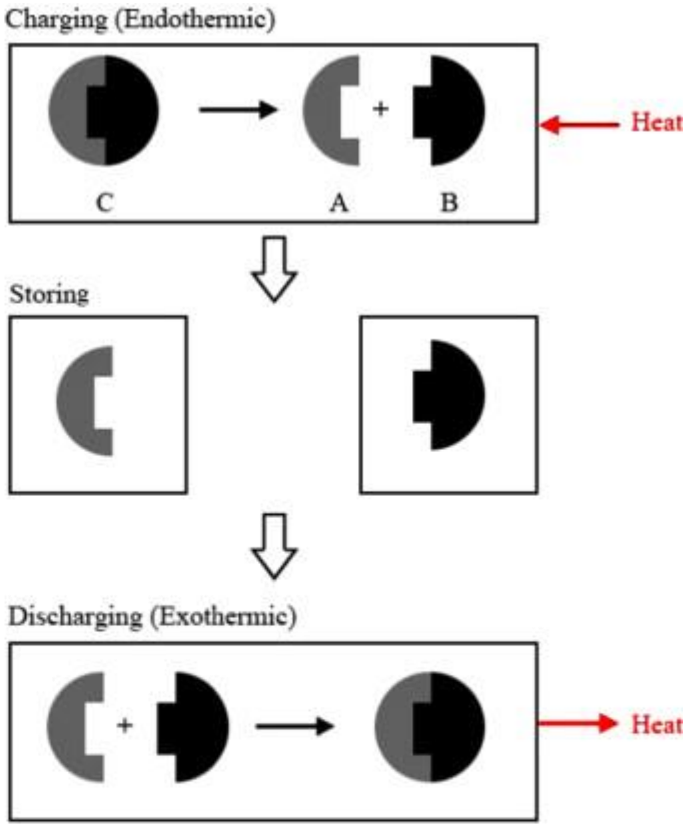

Figure I. 17. Working principle of TCS [38]

I.7.3. Latent Heat Storage

Latent heat storage is the absorption or release of thermal energy of a storage material as it undergoes phase change. The latent heat storage material can be in the form of:

- Solid – Liquid (S-L)
- Solid – Solid (S-S)
- Solid – Gas (S-G)
- Liquid – Gas (L-G)

S-S and S-L materials are commonly used because of the small volume changes while the materials that involve a gaseous state (S-G and L-G) require more energy for the gas compression. Latent heat storage has a higher energy storage density compared to sensible heat storage and also a smaller temperature difference between the storage and release of heat.[39]

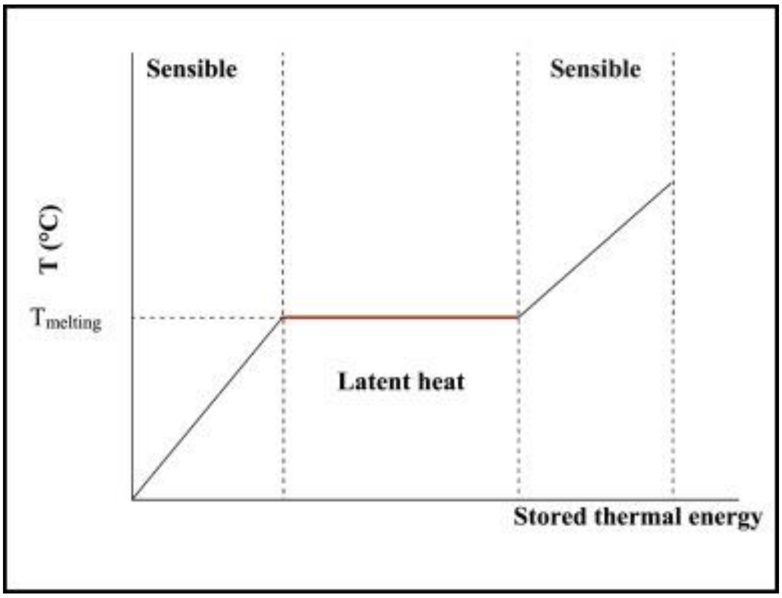

Figure I. 18. Difference between SHS and LHS [40]

The amount of heat stored in a latent heat storage material can be determined by the following equation [34]:

$$Q = m[Cp_s(T_m - T_i) + L + Cp_l(T_f - T_m)] \quad (I.2)$$

Where:

Q – Heat stored (J),

m – mass of the latent heat storage material (kg),

Cp_s – specific heat capacity of the solid material (J/kgK)

Cp_l – specific heat capacity of the liquid material (J/kgK)

T_m – melting point temperature (°C)

T_i – initial temperature (°C)

T_f – final temperature (°C)

L – latent heat of fusion (J/kg)

A latent heat storage system is therefore made up of three major components:

- A phase change material (PCM)
- A suitable heat exchange surface
- A container compatible with the PCM

I.8. Phase Change Materials (PCMs)

The heat storage materials used in latent heat storage systems are called phase change materials. These materials depend on the surrounding temperatures. For Solid – Liquid PCMS, the material is in liquid phase when the surrounding temperatures are higher than its melting point temperature and in solid phase when the temperatures are lower.

During this phase change, the material absorbs heat as it melts and releases heat as it solidifies. This is an effective way of storing thermal energy as PCMs have a high energy storage density per unit mass per unit volume at almost a constant temperature [41].

I.8.1. Classification of Phase Change Materials

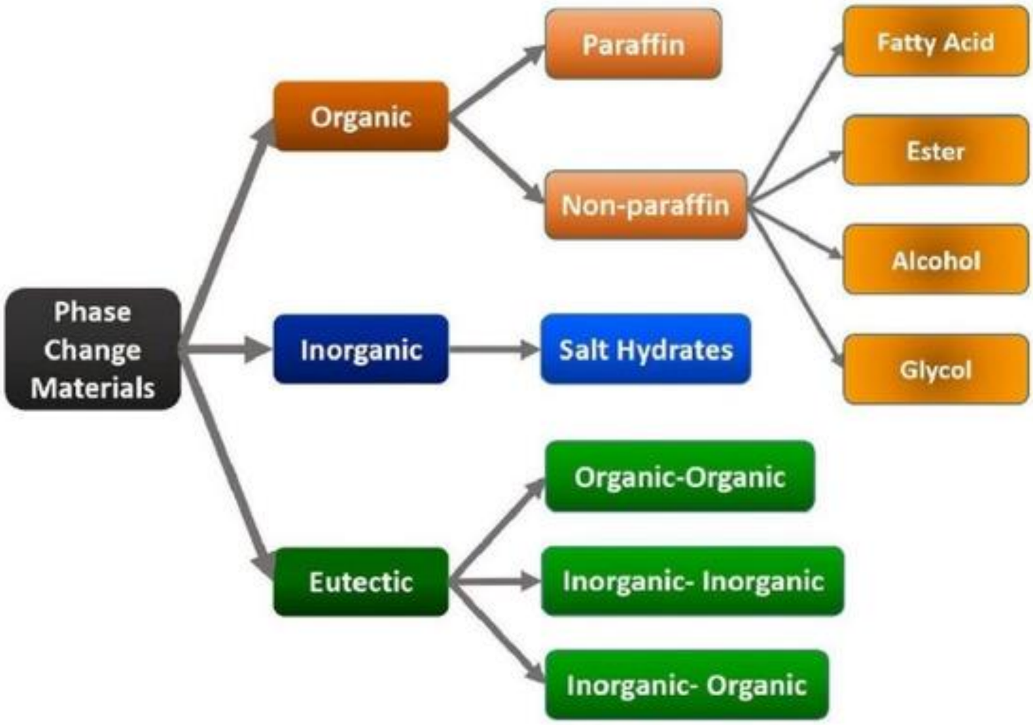

Figure I. 19. Classification of PCMs [42]

I.8.2. Organic PCMs

These are hydrocarbons classified into two groups; paraffin and non paraffin PCMs.

I.8.2.1. Paraffin

Paraffin wax is a mixture of straight chain n-alkanes ($CH_3(CH_2)_nCH_3$). The crystallization of the methyl groups ($-CH_3$) causes the release of high latent heat. Paraffins have a melting range between 20 and 70°C and the longer the chain, the higher the melting point and the latent heat of fusion. Paraffin is cheap and non-corrosive but it has a low thermal conductivity and is slightly flammable [43].

I.8.2.2. Non – paraffins

These are the commonest phase change materials used. They consist of fatty acids, esters, alcohols and glycols and unlike paraffins which have similar properties, each non paraffin has its own unique properties.

These material are characterized by high heat of fusion, low flash points and instability at high temperatures. They are also very flammable and should not be exposed to high temperatures [44].

Table I. 5. Advantages and disadvantages of organic PCMs [45]

Advantages	Disadvantages
• No phase segregation • Little or no supercooling • Non – corrosiveness • Low cost • Available • High latent heat • Chemically stable • Non-toxic	• Low thermal conductivity • High volume • Cannot be transported in plastics

I.8.3. Inorganic PCMs

I.8.3.1. Salt hydrates

These are mostly used for high temperature solar applications. They are alloys of inorganic salts and water to form a crystalline solid with a general formula AB.nH$_2$0. The hydrated salt usually melts to two forms in congruent, incongruent or semi-congruent manner:

- A salt hydrate with fewer water moles

$$AB.nH_2O \rightarrow AB.mH_2O + (n-m)H_2O$$

- Its anhydrous form

$$AB.nH_2O \rightarrow AB + nH_2O$$

Calcium Chloride hexahydrate (CaCl2.6H2O) is the most commonly used as it has a practical melting point of 28 to 30°C and a high specific latent heat of 190.8kJ/kg [46].

Table I. 6. Advantages and Disadvantages of salt hydrates

Advantages	Disadvanatages
• High latent heat of fusion per unit volume • High thermal conductivity • Low volume phase changes • Compatible with plastics • Cheap • Availability	• Most melt incongruently • Supercooling • Spontaneity during discharge process • Corrosive • Phase segregation

I.8.4. Eutectic PCMs

This is a combination of two or more PCMs with similar melting points. The combinations can be organic – organic, organic – inorganic or inorganic – inorganic. These PCMs always melt and freeze without segregation and have high thermal conductivities but they are difficult to control for industrial processes [43].

I.8.5. Properties of PCMs

I.8.5.1. Thermo-physical properties [34]

- Melting point: PCMs' melting point should be close to the operational temperature of the system. Since solar dryers operate between 45 and 75°C, the melting point of the PCM should be below 80°C [45].
- High density and high latent heat of fusion which increase the energy storage density
- High thermal conductivity
- Minimal Volume Change
- Congruent melting
- Low vapor pressure
- High Thermal stability

I.8.5.*2.* Kinetic and chemical properties

- Minimal supercooling
- Long-term chemical stability
- Non – toxic
- Low flammability
- Non-corrosive

I.8.5.3. Economic properties

- Low-cost
- Large – scale availability

Literature Review

II.1. Introduction

This chapter provides a critical review of existing research pertinent to the enhancement of drying systems, specifically focusing on strategies employed to improve air circulation and thermal management. It systematically examines previous studies on the application of turbulence promoters, such as dimples, turbulators, baffles, and winglet vortex generators, in heat exchangers and solar air heaters, assessing their impact on heat transfer rates and friction factors. Furthermore, the chapter reviews the integration of Phase Change Materials (PCMs) in indirect solar dryers and hybrid systems, evaluating their effectiveness in extending drying operations and stabilizing temperatures. Finally, it explores various modifications implemented in drying chamber geometries and designs to optimize airflow distribution and overall drying uniformity. This comprehensive review identifies key advancements in the field and highlights existing research gaps that this master thesis aims to address

II.2. Turbulence Promoters

Luo et al. [47] conducted a numerical study to analyze the effects of combining dimples and delta winglet vortex generators on flow structure, heat transfer, and friction factor in a solar receiver channel for Reynolds numbers (Re) ranging from 4000 to 40,000. Three cases were compared: (1) winglets alone (baseline), (2) dimples alone, and (3) a hybrid design combining both. The winglets were tested in inline and staggered arrangements within a channel of dimensions 200 mm (length) × 75 mm (width) × 30 mm (height). Each winglet had a length of 30 mm, a height of 15 mm, and an attack angle of 18°, while the dimples had a protrusion depth of 4.0 mm and a diameter of 20 mm. The streamwise and spanwise spacing between dimples was fixed at 25 mm, and the winglets were positioned 14 mm downstream of the first dimple row. Results demonstrated that dimples altered the flow structure by interacting with the winglet-induced vortices, enhancing thermal performance. The inline dimple-winglet configuration outperformed the baseline, achieving a 36.23% increase in heat transfer and a 36.29% rise in friction factor. The study highlighted the synergistic effect of combining passive roughness elements (dimples) with active vortex generators (winglets) for improved energy efficiency in solar thermal systems.

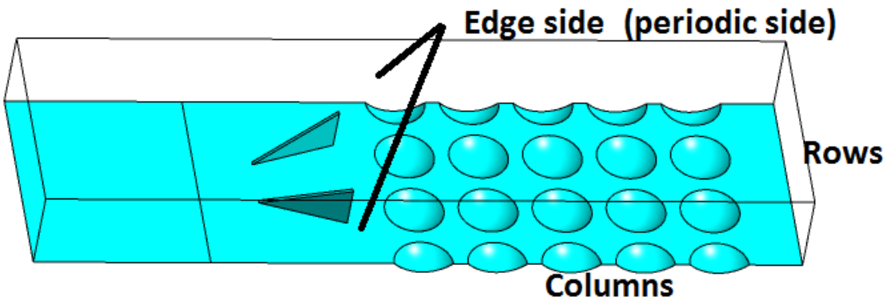

Figure II. 1. Schematic diagram of combined dimples and delta winglet vortex generators [47]

Antony et al. [48] numerically investigated the thermal performance enhancement of a solar air heater using stepped cylindrical turbulators beneath the absorber plate. They used the Thermal Enhancement Factor (TEF) and Thermohydraulic Performance Parameter (THPP) for Reynolds numbers ranging from 3,000 to 24,000 as performance operators. The experimental setup consisted of an air duct with a 380 mm inlet, 1000 mm test section (featuring a 0.5 mm thick copper absorber plate), and 190 mm outlet, where the inlet was 200 mm wide and 30 mm high. The study examined various turbulator configurations, including core diameters (3–7 mm), rows (1–3), relative roughness pitch ratios 11.11, 16.67, 22.22, 27.78 for a 3 mm core diameter with three rows, and step variations (1–3 steps for the same configuration). CFD analysis revealed that increasing the number of steps generated vortices downstream of each turbulator, significantly enhancing the Nusselt number leading to a higher TEF. They concluded that the cylindrical turbulators induced highly turbulent airflow and that optimizing turbulator geometry particularly step count, row arrangement, and pitch effectively boosts heat transfer efficiency in solar air heaters.

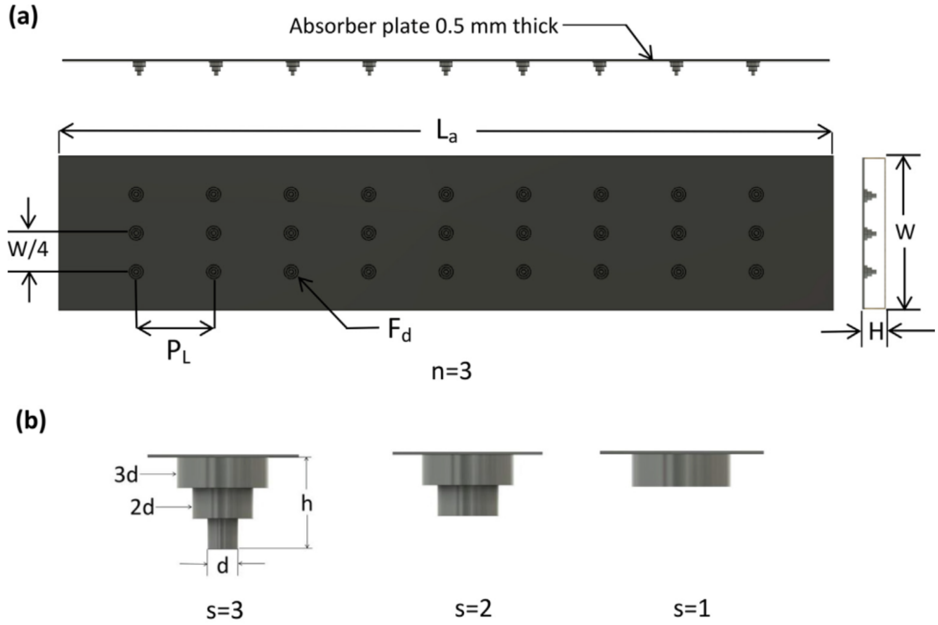

Figure II. 2. Turbulator Configurations [48]

Baissi et al. [49] added two artificially roughened longitudinally curved delta-shaped baffles configurations to a rectangular channel and investigated its thermal performance with Reynolds number ranging from 2500 to 12000. They used perforated and non-perforated baffles arranged in a staggered manner. The relative longitudinal length of the obstacles on the absorber plate Pl/e was from 3 to 5,the relative transversal length Pt/b ranged between 0.6 to 1, relative roughness height (e/H) was 0.8 and single attack angle (α = 45°).The channel was divided in three different sections namely the entrance(600 mm × 450 mm × 25 mm), test(850 mm × 450 mm × 25 mm) and exit sections(300 mm × 450 mm × 25 mm). The obtained results showed that higher heat transfer rates were obtained for perforated longitudinally curved delta shaped baffles than with the non-perforated ones for all the Pl/e and Pt/b ratios used.

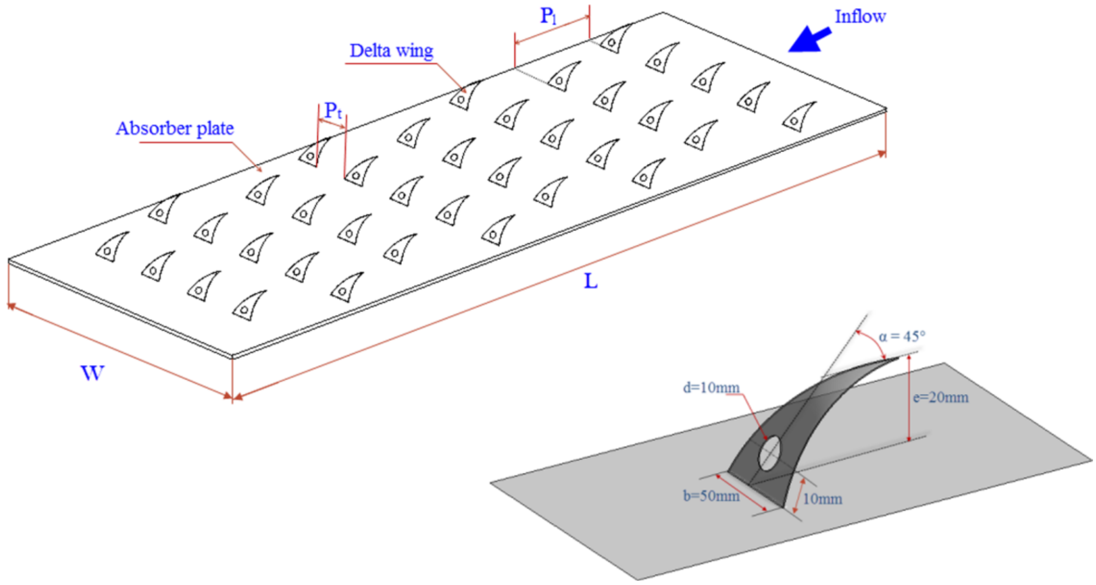

Figure II. 3. Absorber plate with longitudinally curved delta-shaped baffles [49]

Koolnapadol et al. [50] investigated thermal performance of a solar air heater with rectangular-wing vortex generators for Reynolds number ranging from 5290 to 22700. Wings/Winglets are commonly used to improve thermal performance as they generate longitudinal vortices that increase turbulence with a minimum pressure loss. In this study, the rectangular winglets were made of 0.5mm thick aluminium strip with a height of 20mm and width of 30mm. They were placed on the absorber with three attack angles of 30°,45°, and 60°.The longitudinal pitch spacing P_l was 3mm, 4.5mm and 6mm with the relative wing pitches P_R = 1.0, 1.5 ad 2.0. An electrical heater on the absorber provided a maximum uniform heat flux of 200 W/m2. The results indicated that the RWVG caused a high transfer rate that was about 5.79 times compared to a flat plate duct. The RWVG that produced the best overall thermal performance was seen to be at attack angle 60 and P_R = 1.0.

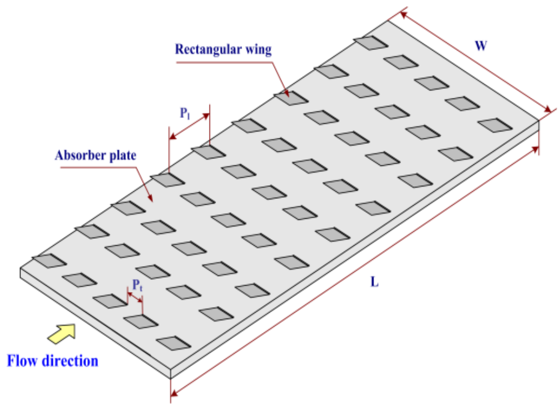

Figure II. 4. Absorber plate with rectangular-wing vortex generators [50]

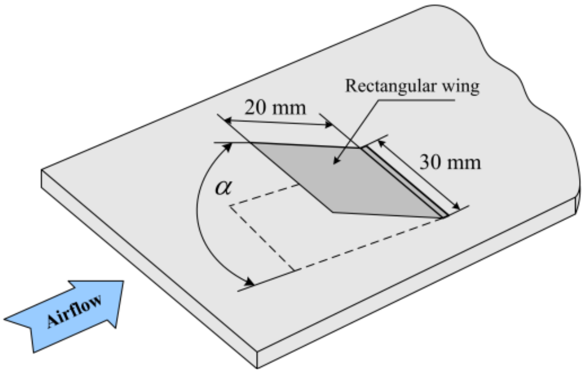

Figure II. 5. Rectangular Wing Vortex Generator [50]

Hassan et al. [51] compared a non-roughened duct with a multiple arc dimple roughened duct and studied the thermal performance improvement basing on the Nusselt number and friction factor. The Reynolds number was ranging from 2000 and 18000. The rectangular duct had dimensions of 2150 x 330 x 30 mm with an entry, test and exit section of length 650, 1200 and 300mm, respectively. The relative roughness pitch of the roughness absorber plate p/e was 4,8,12 and 16. The relative roughness height e/Dh was 0.018, 0.027, 0.036 and 0.045 and relative roughness width W/w was 1-5 with the angle of attack being 30,45,60 and 75. A blower was used to pass the air through the ducts and the absorber plate was heated by solar radiation. The results indicated that for the roughened duct, the Nusselt number increased and the friction factor decreased as the Reynolds number increased.

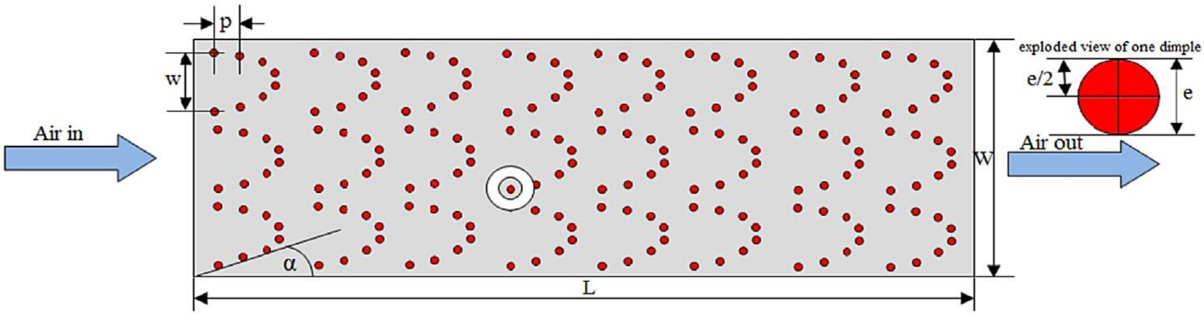

Figure II. 6. Schematic diagram of multiple arc in dimple pattern roughened plate [51]

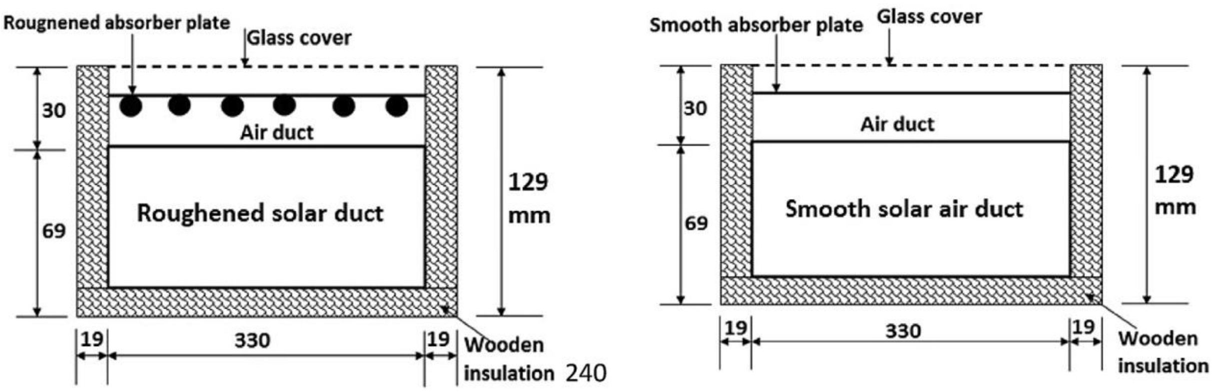

Figure II. 7. Line diagram of roughened and smooth ducts [51]

Promvonge et al. [52] studied how the thermal characteristics of a constant heat fluxed tube were influenced by V-shaped rectangular winglets (V-RW) and V-shaped Delta Winglets (V-DW) arranged at attack angle of 45° with Reynolds number ranging from 4130 to 25900. The winglets were installed at intervals on a straight aluminium tape of 50.8 x 1200 x 0.5mm with four pitch lengths P =100, 75, 50 and 25mm equivalent to relative winglet pitches P_R = P/D = 0.5, 1.0, 1.5 and 2.0. The winglet heights were, b = 5.0, 7.5 and 10 mm corresponding to the ratio of flow blockage, B_R = b/D = 0.1,0.15 and 0.2, respectively. The tape was inserted in a copper tube having 50.8mm inner diameter and 2mm thickness with length of 3000mm and test section being 1200mm long. The results showed that the Nusselt number and friction factor rise sharply with increasing BR but reducing PR for both the winglets with the V-RW giving the higher values.The V-DWs reached the highest Thermal Performance Enhancement Factor of approximately 2.0 at a P_R of 1.0 and a B_R of 0.15, which was about 3% greater than that of the V-RW.

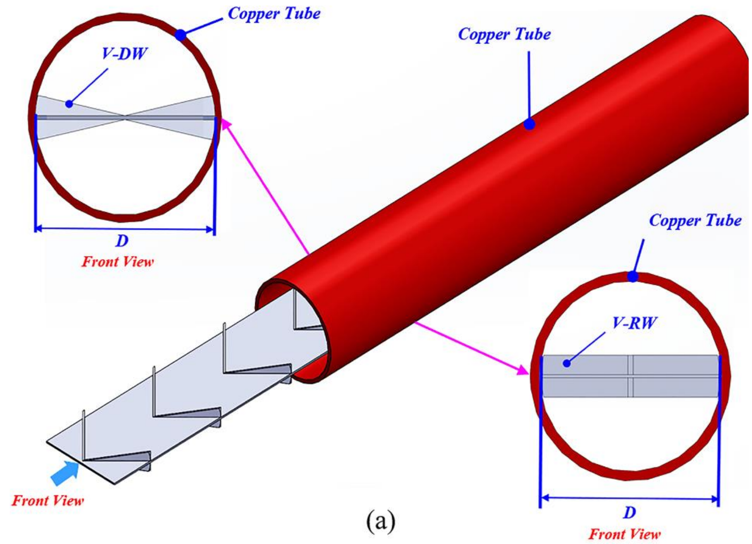

Figure II. 8. Test section with V-WVG inserts[52]

Chu et al. [53] placed various twisted tapes (TTs) configurations in tubes and studied their effect on the thermo-hydraulic performance basing on Nusselt number and friction factor for Reynolds number ranging from 4000 to 10,000. The configurations included successive, U-cut, isosceles V-cut and obtuse V-cut TTs of length 1.0m and thickness 1.0mm. The helical pitch was between 160mm and 320mm with the width of the TTs fixed at 20mm. The twisted ratio Y ranged from 4 to 8. The results showed that there was an improvement of the Nusselt number and friction factor for all the configurations compared to the plain tube.

The successive TTs showed the least improvement as the U-cut and isosceles V-cut configurations had Nusselt and friction factor that was 1.17 and 1.31 times, respectively. The obtuse V-cut configurations had the highest Comparative Thermal Performance of 1.18 to 1.23.

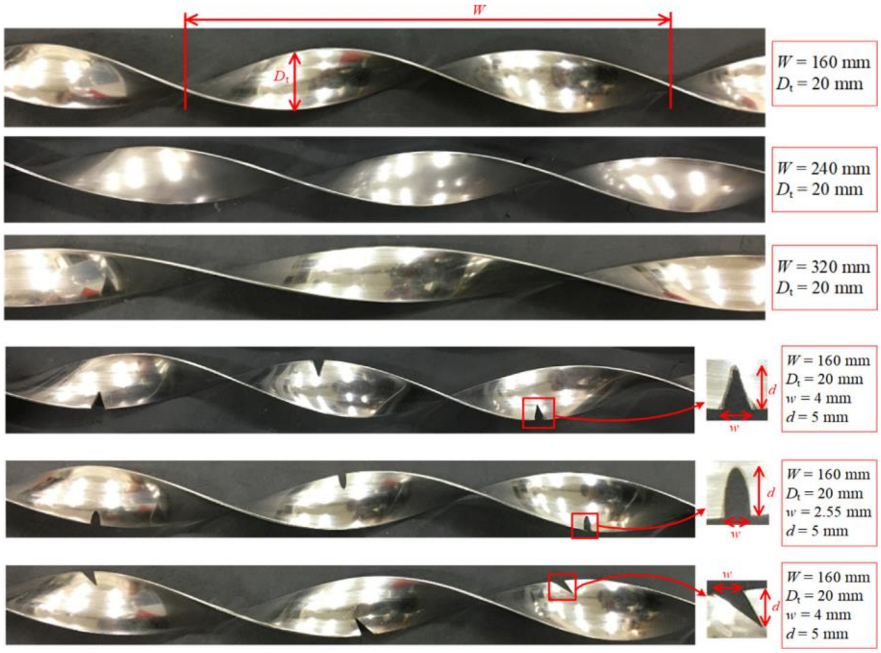

Figure II. 9. Tested twisted tapes with various cut configurations[53]

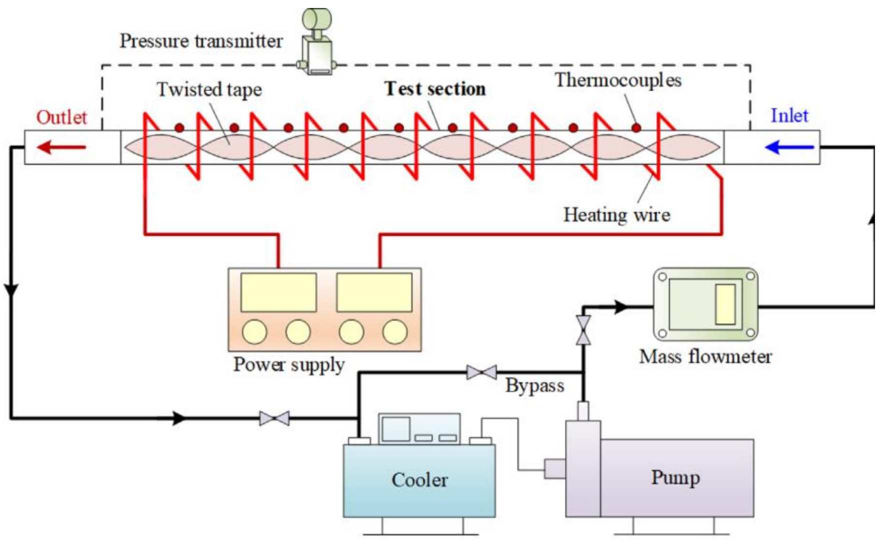

Figure II. 10. Schematic of experimental system[53]

Bader et al. [54] combined transverse ribs (TRs) and delta – winglet vortex generators(DWVGs) in a single-pass solar air heater with an objective of improving its thermal performance. The DWVGs were 50mm long and had a height of 30mm. They were placed 150mm from the plate's edge. The pitch ratio was 10, and the gap between the winglets' tips was 10 mm with an attack angle of 60°.

The TRs had dimensions of 350 x 20 x 30mm with a similar pitch ratio of 10 and attack angle of 90°. The results indicated that the Nusselt number of the artificially roughened solar air heater was 2.35 times higher than that of the smooth air heater.

There was also an increase of 21.2% of the thermal efficiency of the solar air heater when the ribs and winglets were combined.

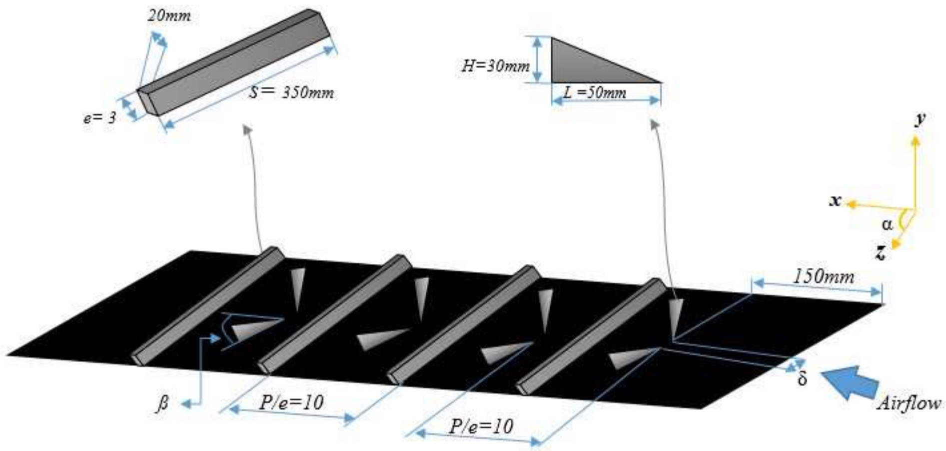

Figure II. 11. Schematic view of the combined artificially roughened solar air heater[54]

II.3. PCMs in indirect solar dryers

Singh and Mall [55] developed a natural convection indirect mode solar dryer with paraffin wax as phase change material to dry banana slices. The drying system consisted of a solar collector with PCM and a drying chamber. A paraffin wax layer of 1cm thickness was placed between the casing bottom and absorber plate of the solar collector. The PCM was put in use for 5h after sunset which enabled the drying of 400g of banana slices from 73.2% (wb) to 20% (wb) in 18 hours . An average drying rate of 0.13 kg of water/ kg was of dried product/h was calculated with a maximum and average drying efficiency of 9.88 and 2.98%, respectively.

Figure II. 12. Experimental setup of indirect mode solar dryer[55]

Lad et al. [56] measured the time taken to dry ginger, hot yellow pepper, onion, sweet green pepper and tomato to a 10% final moisture content at 50°C temperature in an indirect solar dryer. The CFD study was done on three different configurations of the dryer; a conventional indirect solar dryer as case 1, indirect solar dryer with 25kg of paraffin wax-6035 as PCM inside the solar collector as case 2 and case 3 with the PCM placed in aluminum containers inside the drying chamber. The temperature in the drying chamber was maintained at approximately 50°C in all three cases. Sodium chloride was used as dehumidifier the drying chamber. The drying kinetics showed that drying time was significantly reduced for solar dryers with PCM. It was also observed that the best performing solar dryer was case 3 with PCM inside drying chamber.

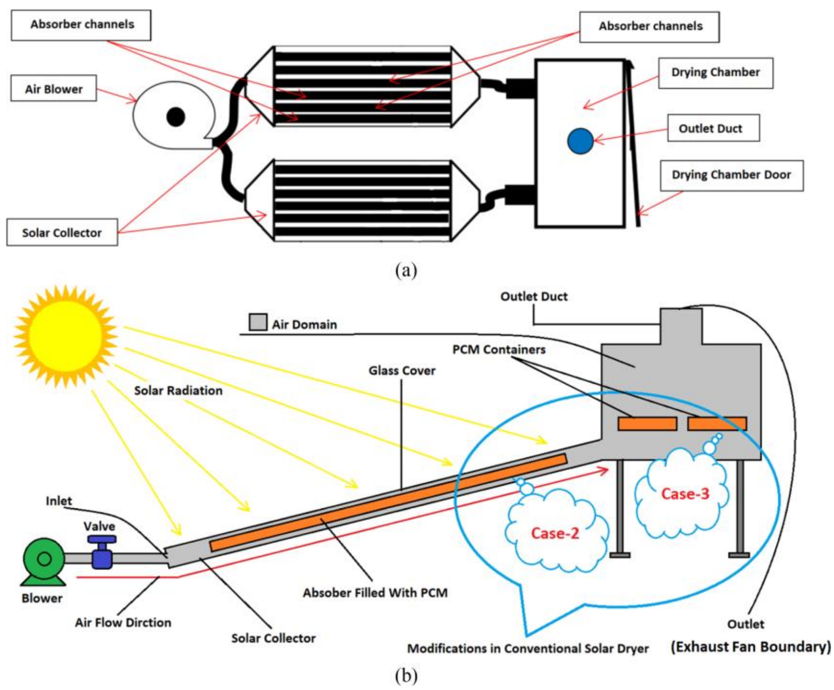

Figure II. 13. (a) Schematic diagram of conventional indirect type solar dryer (top view) (b) Modifications in solar dryer as per considered cases[56]

Behera et al. [57] designed a hybrid solar dryer to conduct an experimental analysis on the drying of tomatoes, potatoes, bitter gourd and green bananas. The system consisted of a fin-based solar collector and a drying chamber with electrical components like solar photovoltaic panel. 60 rectangular fins were placed on the absorber of the solar collector as turbulators. 5 kg of silica gel was added at the entry and bottom of the drying chamber to reduce on the humidity of the air in circulation. 3kg of paraffin wax was added at the bottom of the absorber plate in an aluminium container to provide heat during the night and cloudy weather. It was observed that the addition of the turbulators and desiccant without the PCM led to the improvement of the drying efficiency, collector efficiency and drying rate by 64.737%, 33.61% and 1.351 kg/hr, respectively. The addition of the PCM led to a further increment of 6-8%, 4-5% and 27-30%.

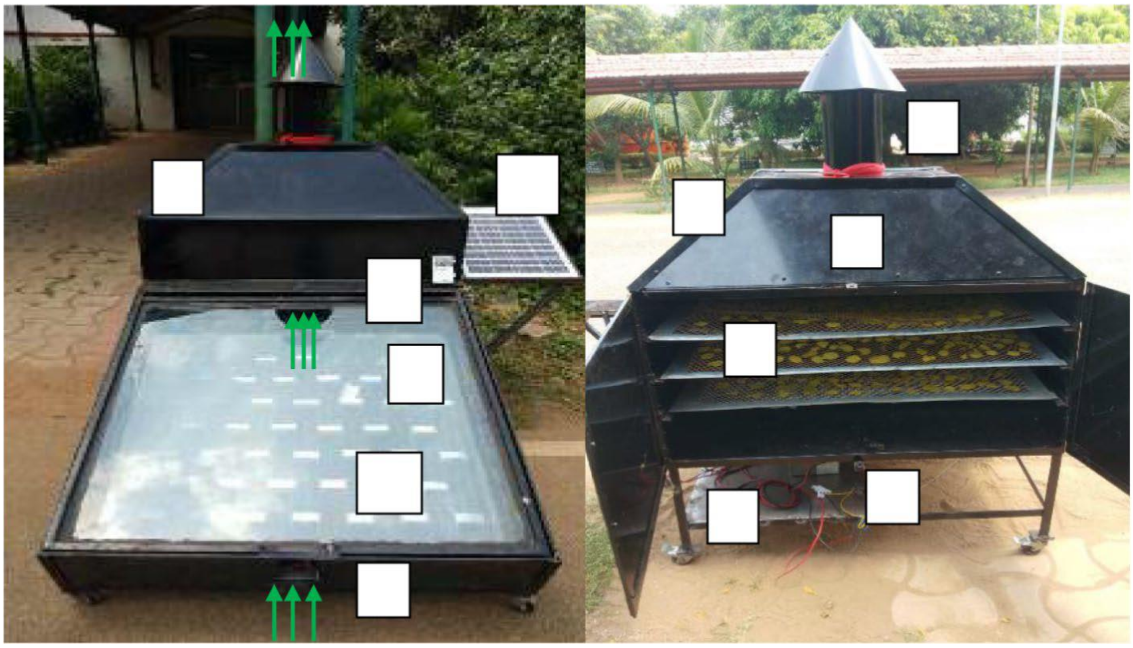

Figure II. 14. Experimental setup of hybrid dryer[57]

Gilago et al. [58] studied drying kinetics of carrots using a passive indirect solar dryer in two setups: without TES (setup-1) and with paraffin wax as TES (setup-2). The system consisted of a solar air collector and a 4-tray drying chamber with a chimney. The second setup had a transparent polycarbonate rectangular unit with 50 concentric aluminium fins filled with paraffin wax. The TES unit was placed below the first tray in the drying chamber. Results showed that setup 2 achieved an improvement in drying efficiency and drying rate of 38% and 18.3%, respectively compared to setup-1. The second setup also showed a higher specific moisture extraction rate of 3.31 kg/kWh with a 92% reduction in energy consumption.

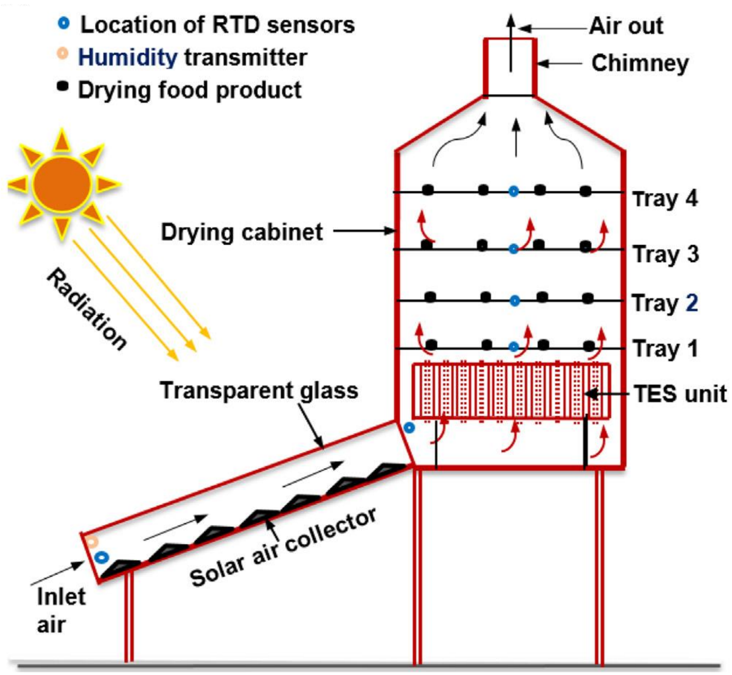

Figure II. 15. Schematic representation of solar drying unit[58]

Figure II. 16. Photo snapshot of (a) inside view of setup-II, (b) sliced carrot slices and (c) dried carrot slices[58]

Kondareddy et al. [59] designed a modified force convection solar dryer (MFCSD) in order to dry elephant apple slices. The system consisted of a drying chamber, a primary conventional solar collector and a secondary collector having an energy storage unit with paraffin wax PCM – OM – 50 as PCM. An aluminium sheet was added in the primary collector to create a zig-zag path to speed up thermal conductance. The paraffin wax was placed in 50 aluminium tins and aluminium strips were added then placed in the collector. The drying chamber had an inbuilt thermal collector as well as 2 kg of silicone gel bed. The performance analysis of the MFCSD showed an improvement of thermal efficiency of the collectors, drying time and exergy efficiency by 12%, 30-45% and 78%, respectively compared to a conventional dryer.

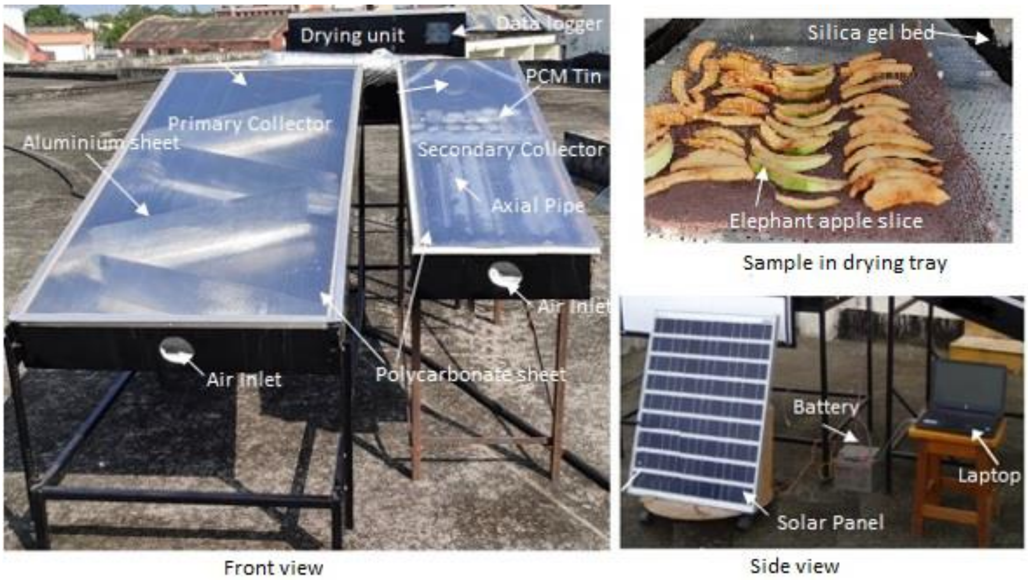

Figure II. 17. Photographic view of modified forced conventional solar dryer [59]

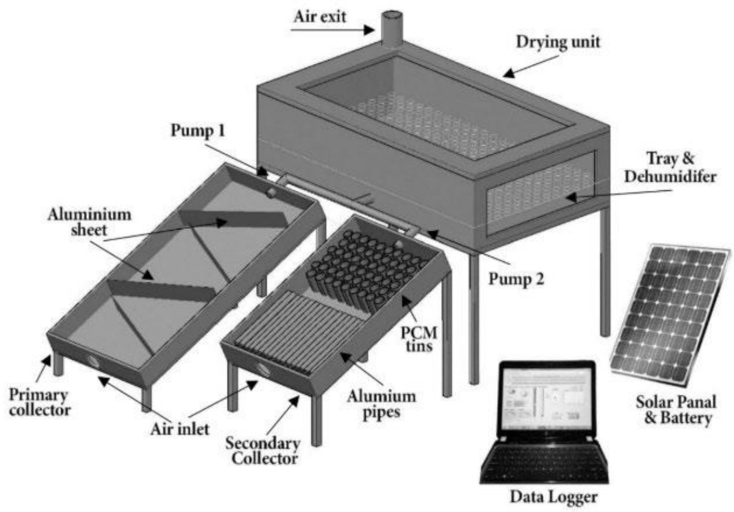

Figure II. 18. Schematic diagram of modified forced conventional solar dryer[59]

Baddadi et al. [60] conducted a comparative analysis of four collectors: a flat solar collector, solar air collector with $CaCl_2.6H_2O$ as latent heat storage, another solar air collector with 60kg paraffin as PCM and a heating unit combining the two collectors with the PCMs. The objective was to create an innovative indirect forced convection dryer system having two solar collectors integrated with two different PCMs. The $CaCl_2.6H_20$ was placed in spherical nodules made of black polyolefins and then arranged in 25 rows and 12 columns on the absorber plate of the collector. Additives were added to the $CaCl_2.6H_20$ to prevent its supercooling. The collectors completed a system that consisted of a drying chamber, a small PV panel to cover electrical demand and a battery to store the excess electrical energy.

The system showed an annual energy, energy payback period and total embodied energy equal to 640kWh/year, 2.5 years and 1654.25 kWh, respectively with a payback period of 1.39 years.

Figure II. 19. Indirect forced convection dryer system having two solar collectors integrated with two different PCMs[60]

Baddadi et al. [61] studied the influence of solar air heater integrated with PCM on the microclimate of a hydroponic greenhouse. The solar collector had two stacked beds having spherical nodules containing Calcium Chloride Hexahydrate as the PCM. It was connected to the galvanized steel structure greenhouse through a funnel and provided latent heat during the night. During night time, the temperature of the greenhouse fitted with the solar air heater had temperature ranging between 17 and 20°C which was over 6 °C higher than the usual nocturnal temperatures of the greenhouse. This improvement indicated that solar heating with thermal storage was better than the other conventional heating systems used to maintain the nocturnal temperatures of greenhouses.

Figure II. 20. Hydrophonic greenhouse with PCM[61]

II.4. Drying chambers with modifications

Tuncer et al. [62] designed a convex – type solar absorber assisted dryer to dry municipal sludge. The aluminium absorber had a top and bottom diameter of 0.22 and 0.35m respectively with 16 holes of 15mm diameter created on it. A fan was placed at the bottom of the absorber to supply the hot air to the drying chamber that was connected to a single – pass air collector. The novel system was compared with a conventional dryer and the thermal performance studied. The convex solar absorber provided high flow rates and high temperatures in the drying chamber that decreased the drying time by 31-35% with an increase of 51% in energy efficiency.

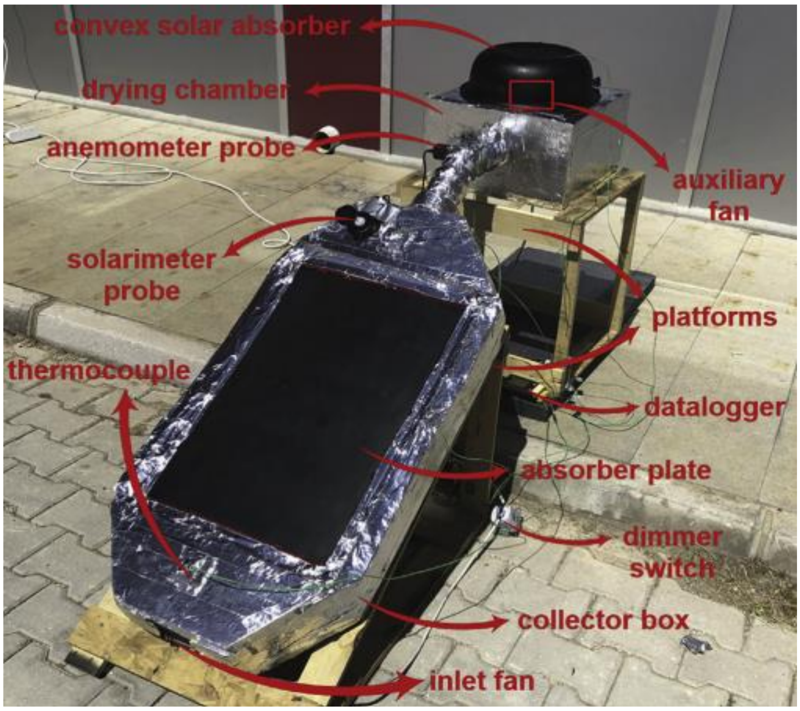

Figure II. 21. Convex – type solar absorber assisted dryer[62]

Babu et al. [63] designed four different geometries of a drying chamber using CFD to dry leaves. The dimensions taken into consideration were the air inlet and outlet sizes, location of the outlet, distance of the tray from dryer ceiling, depth of the tray and its area. The objective was to create an optimal appropriate geometrical shape of drying chamber that enables uniform distribution of drying air with a minimal pressure drop between inlet and outlet of drying chamber. Minimum pressure drop and maximum moisture removal was observed in configuration (d) which had trays in series.

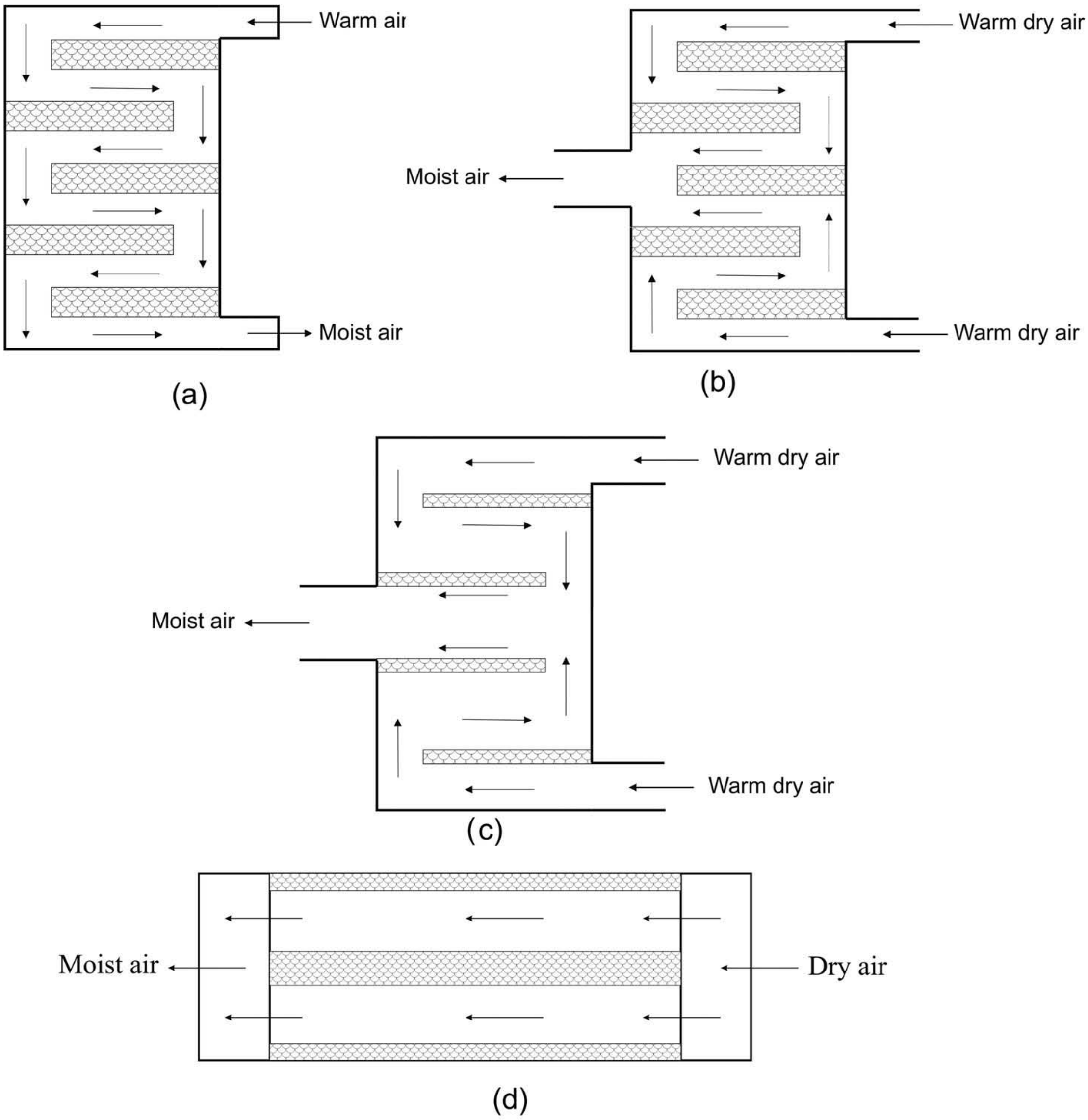

Figure II. 22. Various configurations of the drying chamber[63]

Al-Kayiem et al. [64] designed a multi chamber drying cabinet consisting of three separate chambers with an angular movable tray for a hybrid solar thermal dryer. The objective was to study the effect of tray inclination angle, air velocity and turbulence intensity distribution in the drying cabinet. The cabinet consisted of an entrance part, drying section and updraft tower. The drying section was divided into three sections each having a tray. The trays were positioned at 0,10,20 and 30° relative to the horizontal. The tray inclined at 30° showed the best flow and drying uniformity. The multi chamber cabinet showed improved velocity distribution and flow characteristics compared to conventional cabinets.

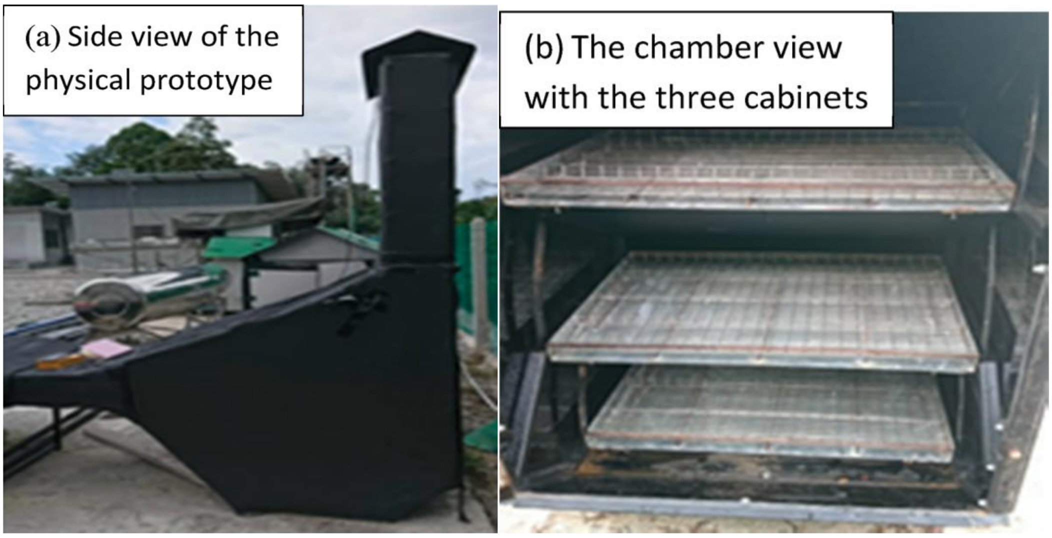

Figure II. 23. Experimental prototype of the multi-chamber drying cabinet [64]

Phoosomma et al. [65] modified the drying chamber of a hybrid solar system to dry cucumber, broccoli, gourami, carrot and pumpkin. The drying chamber had a length of 70cm, width of 100cm and a height of 120cm with a glass cover. They placed pulsed copper heating pipes at the bottom of the chamber to radiate heat from hot water stored in a water tank. The entire system consisted of solar panels, solar collector, water tank and the drying chamber. The modification led to increase in the chamber's temperature within two minutes giving an average temperature of 49.43°C with a maximum drying efficiency of 36.08%.

Figure II. 24. Experimental setup of Innovative hybrid drying system[65]

Figure II. 25. Pulsing heat pipes' placement[65]

Jamal et al. [66] Created four outlets at the bottom of a drying chamber of a natural convection indirect solar dryer and observed their effect on the drying rate of the dryer. The chamber had dimensions of 50 x 50 x 50 cm and was made of steel with an insulated interior. Three shelves to accommodate the product were placed inside. The holes at the bottom had a diameter of 10cm. 3 variations were used simultaneously; fully closed, two holes open and all four holes open. The fully open variation had the highest drying rate and efficiency of 0.066kg/s and 31.86%, respectively while the fully closed variation had the lowest drying rate and efficiency of 0.057 kg/s and 27.59%, respectively.

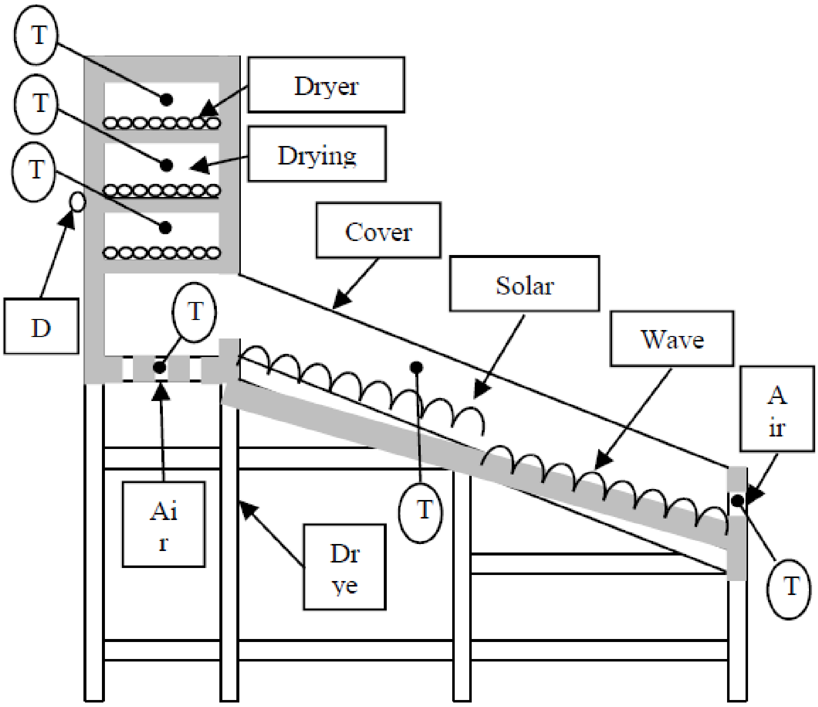

Figure II. 26. Drying chamber with outlets at the bottom[66]

Sileshi et al. [67] carried out a CFD study on the effect of a vertical air distribution channel in the drying chamber of a mixed mode solar dryer. The chamber had 4 vertical levels of mesh trays of size 1m x 1.1m x 0.7mm. The distribution channel was made of galvanized sheet metal of length of 1.5m and width of 1m with an air supply opening size of 0.1 x 1m. The chamber was made of plywood with a transparent top and of size 1.5 x 1 x 2.2m. The study revealed that the vertical air distribution enabled uniform air flow and recirculation in the drying chamber as there was a steady uniform velocity distribution of 0.11m/s over all the drying trays after 20 minutes. A uniform relative humidity distribution differing by 2% across all the trays was also observed which showed that air stagnation was not taking place in the chamber.

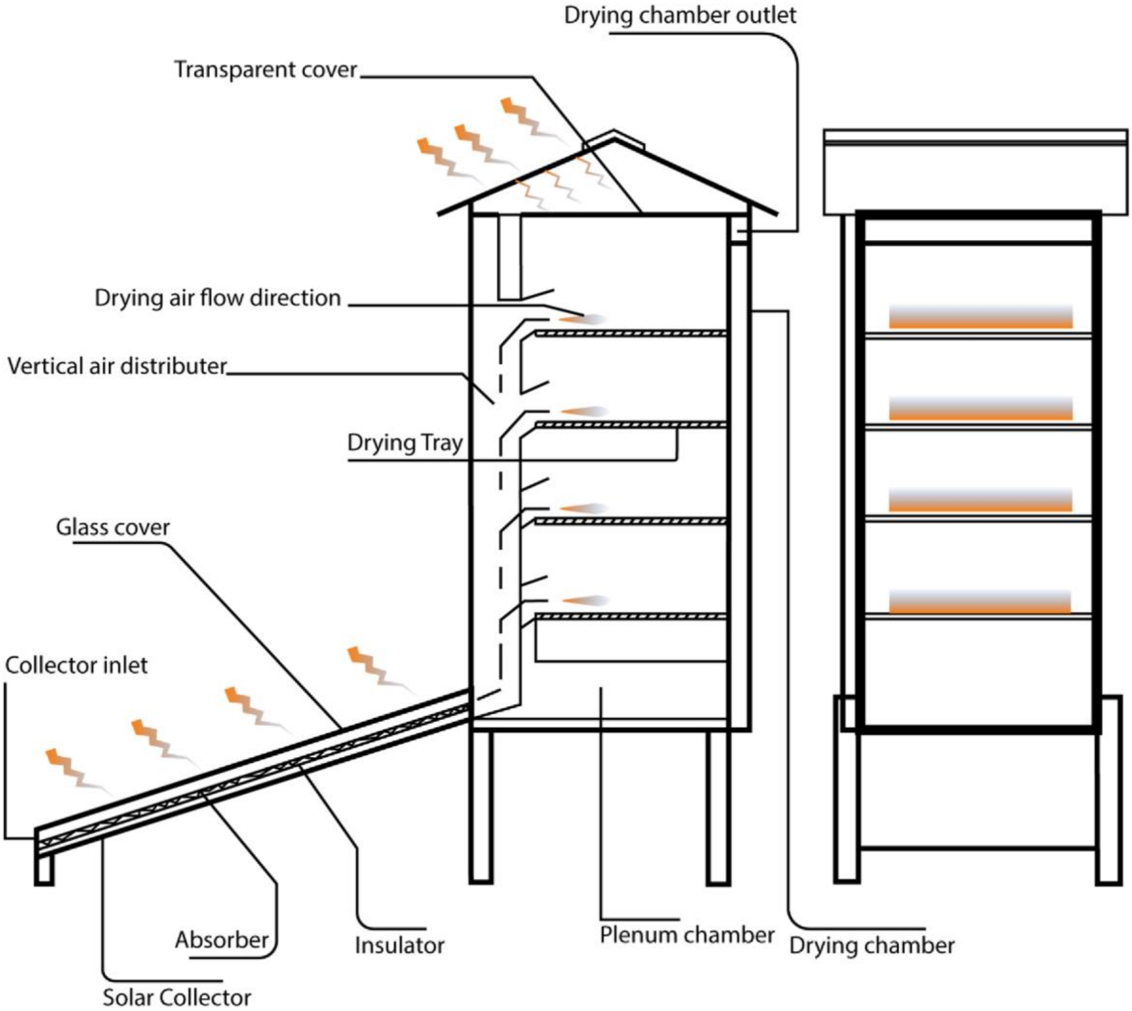

Figure II. 27. Schematic diagram showing the dryer with air distribution system[67]

Azmi et al.[68] added an inclined slotted angle air distributor to a swirling solar drying chamber and studied its effects on the drying of kaffir lime leaves. The stainless-steel drying chamber had a diameter and height of 0.5m. The air distributor was placed at the bottom of the chamber and had an inclined slotted angle of 67.5°. It was made of LB PLA filament and had a thickness and diameter of 0.01 and 0.02m, respectively. The system had a fast drying period and efficiency of 4.2 hours and 11%, respectively compared to a conventional solar drying chamber which had a drying period and efficiency of 5.8 hours and 9.1%, respectively.

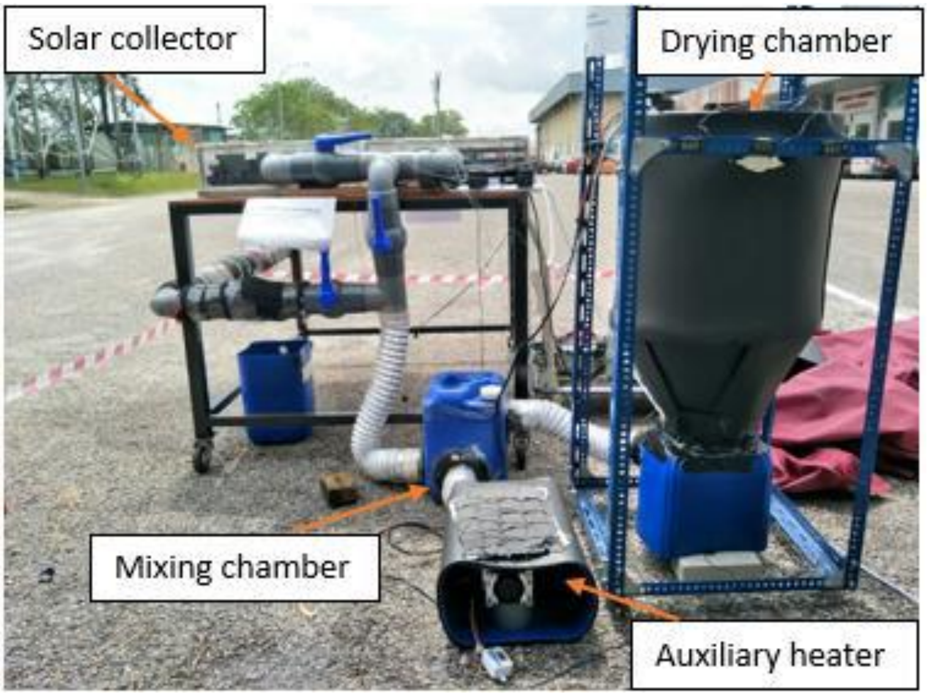

Figure II. 28. Experimental setup of solar drying system swirling drying chamber[68]

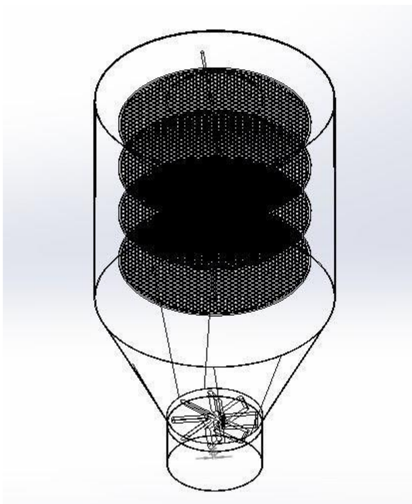

Figure II. 29. Details of the swirling solar drying chamber with inclined slotted angle air distributor installed at the bottom of the chamber[68]

General Conclusion

General conclusion

This Master thesis embarked on an experimental and numerical investigation to optimize air circulation and enhance the overall performance of a mixed solar drying cabinet, addressing critical challenges associated with uneven drying and the intermittency of solar energy. Conducted at the Renewable Energy Research Center in Ghardaia, Algeria, the study systematically explored the integration of turbulence generators and Phase Change Materials (PCMs) within the drying chamber. The objectives included quantifying the impact of these modifications on drying kinetics, thermal stability, and economic viability, while also leveraging numerical simulations to provide a deeper understanding of the underlying thermofluidic phenomena.

The experimental results unequivocally demonstrated the substantial improvements achieved through the implemented modifications. The strategic integration of turbulence generators, proved highly effective in enhancing air circulation and accelerating the drying process. Compared to the baseline configuration, the enhanced chamber reduced the drying time for pepper. Even more significant improvements were observed with the second enhancement. These findings highlight the critical role of induced turbulence in facilitating efficient convective heat and mass transfer.

Furthermore, the study successfully demonstrated the benefits of integrating Phase Change Materials (PCMs) for thermal energy storage. The use of hydrated calcium chloride ($CaCl_2 \cdot 6H_2O$) as a PCM effectively stabilized the drying chamber temperature, mitigating the fluctuations inherent to solar energy availability. During periods of low solar radiation or at night, the PCM maintained the chamber temperature higher than the ambient environment, thereby extending the effective drying hours and contributing to a more continuous process. The analysis of drying kinetics revealed a significant increase in the effective moisture diffusivity across all modified configurations.

The numerical simulations provided crucial insights that corroborated the experimental observations. The CFD results visually confirmed that the turbulence generators, particularly the winglet rods, significantly improved airflow distribution, promoted turbulent mixing, and led to more uniform temperature fields within the drying chamber. These simulations elucidated the complex fluid dynamics and heat transfer mechanisms, validating the experimental findings and offering a deeper understanding of how these internal modifications enhance overall system efficiency.

From an economic perspective, the optimized mixed-mode solar dryer demonstrated compelling viability. The system's low capital investment, coupled with reduced operational costs due to reliance on solar energy, resulted in a remarkably short payback period.

In essence, this research provides robust evidence that the strategic integration of turbulence generators and Phase Change Materials is a highly effective approach to optimize the performance of mixed solar drying cabinets. The findings offer practical and economically viable solutions for improving drying efficiency, ensuring product quality, and extending operational periods, thereby contributing significantly to sustainable agricultural practices and food preservation in arid and semi-arid regions.

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