

Solar Energy Kinetics and Trends for Optimum Food Dehydration

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Abstract

The effectiveness of drying depends on the design of the drying equipment. Several design configurations were examined for their performance in terms of heat flow and air velocity distribution across the trays. Of all the configurations investigated, the distributed-type active solar dehydrator- design that have supply of airflow across the trays horizontally provides the best performance in airflow and temperature distribution. Spatial configuration of air inlet and outlets in a solar dehydrator affects its performance. In a drying equipment such as the cabinet type dehydrators, it is expected that the food items placed on the trays receive relatively equal amounts of the inlet heat and airflow. To achieve such results in a solar dehydrator, the heated air should be made to flow horizontally across the trays while exiting through vents on the opposite end of the inflow. When such configuration is not implemented, drying with the equipment will be inefficient.

Keywords: Computational, drying, dehydrator, flow, kinetics, Solar Energy, trends.

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I. Introduction

Energy in our solar system is produced mainly by the Sun. Solar power is responsible for sustaining life on earth. [1] note that energy comes to the organism from sunlight. Solar power and energy resources on our planet are enormous, eco-friendly and virtually inexhaustible. Solar energy drives other renewable energy sources such as wind, hydropower, animal power and biomass. Outside our atmosphere, the intensity of solar power is more than 1 kW.m⁻² emitted continuously. On the earth's surface, the average daily interception of this enormous amount of power is 4 kWh.m⁻². The amount of solar energy intercepted in less than one month by the earth is equivalent of all the energy that is originally stored in coal, natural gas and petroleum available on the planet.

The solar constant – the amount of energy arriving the earth's atmosphere from the sun – is approximately 1367 W.m⁻². This amount varies over time due to variations caused by solar flares and sunspots. For daily record, the solar constant, I_o is calculated using Equation 1[1].

$$I_o = 1367(1 + 0.034 \cos(2\pi N/365))$$

Equation 1

where N is day number of the year (obtained from the Julian date calendar)

Due to constraints arising from absorption and diffraction of the sunlight in the earth's atmosphere, variations in weather, loss of sunlight at night, the amount of solar energy (average insolation) reaching a given location on earth is lower than the amount outside the atmosphere.

For thousands of years – since mankind began interacting with inanimate objects in search for comfort, solar heat has been used in various forms for different purposes. Such purposes include for space and water heating, cooking, and electricity generation. Although solar power on earth on a daily basis is enormous, its availability

is not instantaneous at all times and seasons. Also, it is not useful at large scale at several locations on earth. For this reason, it must be captured at suitable temperature, transported and possibly stored for later use [1]. Open sun drying is one of the oldest forms of preserving agricultural produce by spreading it in the sun for several hours for water to evaporate from it. Although still practiced in many parts of the world today, it is saddled with lots of disadvantages; namely: exposure to insects, rodents and livestock, dust contamination, long drying duration and low quality of produce [2],[3].

Solar heating is widely applied in crop drying in agriculture, in water and space heating, growing food in greenhouses, producing salt from evaporated sea water, cooking and electricity generation. The solar heat is available in nature as diffuse and temporarily available. There is no location on earth that receives solar power in a continuous and predictable quantity. Such is only possible in space. It therefore requires large collection areas to capture sufficient heat energy and convert same to heat. The heat captured is sometimes stored in thermally insulated enclosures until when needed. Such storage facilities are designed with effective controls to prevent waste of the energy captured [1].

Different designs of solar collectors have been designed for various purposes. Their efficiencies have been studied by researchers across the world. There are two main types of solar collectors: stationary (non-concentrating) and concentrating solar collectors. The non-concentrating collectors use the same area for receiving and absorbing solar radiation; whereas concentrating collectors focus the solar energy to a smaller receiving area; resulting in an increased radiation flux. The concentrating collectors are suitable for high temperature applications, such as in furnaces or power generation, while non-concentrating collectors are suitable for low power applications such as in drying agricultural products [4].

Stationary solar collectors do not track the sun (as the name suggests); but are permanently fixed in position to capture solar energy. There are three types of solar collectors in this category namely: flat plate, stationary compound parabolic collectors, and evacuated tube solar collectors. The ideal collector angle (tilt) for maximum solar gain for a year is typically computed by subtracting 15 degrees from the latitude of the location. However, in practice, any angle from 10° to 30° can be used for solar collectors designed for food dehydrators. Other angles between 0° and 90° can still be used, but issues such as draining of rainwater from the panel need to be considered.

Flat plate collectors are the simplest of solar collector designs. They are mostly used in drying as well as living space and water heating. The basic form of a flat plate collector is a compartment that has a dark surface – for efficient heat absorption – and a means of transporting the collected energy with minimal loss to the location where the energy can be used immediately or stored for later use. The liquid tubes are connected at both ends to large-diameter header tubes. An alternative design is the serpentine design – in which a wavy pattern is used to pass liquid from one end of the panel to another. Unlike the header-riser design, the serpentine design provides uniform flow distribution, but cannot work effectively with natural circulation; a pump is needed to circulate the heated liquid. [4],[5] listed the requirements:

- i. A black-painted surface – for the purpose of absorbing most of the incident energy from the sun.
 - ii. Glazing sheet(s) to allow much of the heat to be transmitted readily to the absorbing plate; while preventing significant heat losses by radiation or convection to the surrounding.
 - iii. A duct or tubes to transport the working fluid that carries the heat away from the collector area.
 - iv. An encasement to hold the components of the collector and provide protection against bad weather.
 - v. Insulation built into the encasement to minimise heat loss below or on the sides of the collector plate.
- The glazing material used on the panel is usually from glass material rather than plastic – due to its ability to withstand harsh temperature and surface degradation. Transparent plastics may however be used. Also, unlike plastics, glass does not lose transmittance. Glass materials with low iron content is found to transmit more radiation from the sun – especially up to 3 μm (infrared) in the solar electromagnetic spectrum. Such collectors have improved efficiencies than others. Higher efficiency implies less panel required; this may minimize cost of the glass used [1]. Figures 1, 2 and 3 show the different designs adopted in flat plate solar collectors.

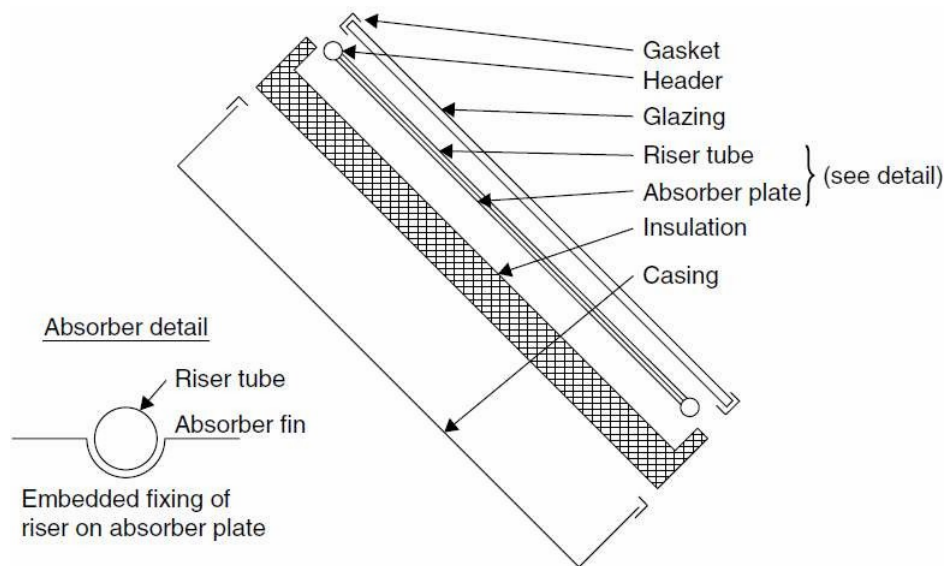


Figure 1: Water-type flat plate collector [4]

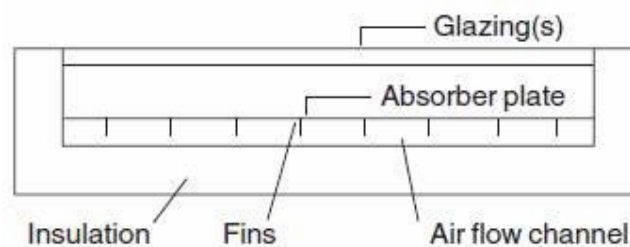


Figure 2 Air-type flat plate collector [1]

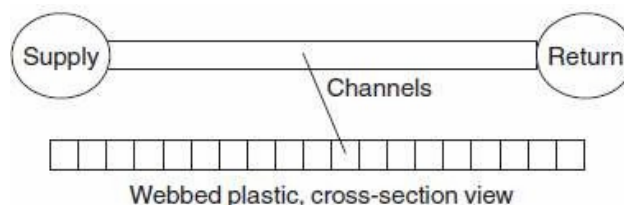


Figure 3: Unglazed water (swimming pool) type collector [1]

The water-type collector in Figure 1 uses water as the working fluid. This has many advantages namely:

- i. Water has relatively high volumetric heat capacity ($4186 \text{ kJ m}^{-3} \text{ K}^{-1}$ at 25°C) and high specific heat ($4.186 \text{ kg}^{-1} \text{ K}^{-1}$ at 25°C).
- ii. It is relatively incompressible.
- iii. Its relatively high mass density permits the use of small tubes and pipes for transport.

In cold climates however, water can freeze during the winter leading to damage of the piping system and the solar collector itself. This can be controlled by using antifreeze such as ethylene glycol or propylene glycol mixed with water. In such cases however, the concentration of components mixture should be optimized to suit specific conditions. The antifreeze degrades with time; hence, replacement is recommended at least every five years. Alternative working fluids that have been used in flat plate collectors include refrigerants and liquids

that change phase. Such have low boiling point and high energy density; consequently, these fluids prove beneficial in scenarios with physical constraints necessitating the transfer of substantial heat with small fluid volumes. They exhibit rapid responsiveness to collector temperature fluctuations, and certain refrigerants resistant to freezing are accessible. Although hydrocarbon oils and silicones can serve as heat transfer oils in collectors, their elevated viscosities lead to increased pumping volume, energy consumption, and overall costs in certain instances as in Figure 1.

The solar collectors which use air as working fluid for heat transfer are used in drying and space heating. Most applications require the use of a fan to move the air across the solar collector to the drying chamber. Passive collectors, particularly in building systems, are designed to facilitate the movement of warm air to the heated space through thermal buoyancy. Simultaneously, there is a return flow of cooler air within this system. The rate of heat transfer by convection from a solid to air is significantly less vigorous than it is from solid to a liquid. Fins are incorporated into air-based solar collectors to improve convective heat transfer, as depicted in Figure 2.

Unglazed solar collectors in Figure 3 are used when Heating water for aquaculture facilities or supplying warm water for showers in camping facilities. Such collectors are fabricated with channelized panels of black plastic. They are highly efficient and less expensive than conventional solar collectors. The reason for their high efficiency is due to the fact that there is no loss of solar energy when passing through glazing, and ambient air can serve as a supplementary heat source when outdoor temperatures are higher than those of the solar collector collar. Such cases arise during hot weather [1].

The material used for absorber plates should be thin metal sheets (such as copper or aluminium) that have high thermal conductivity. Such materials are painted black to ensure maximum heat absorption – with solar absorptance values over 0.95. Nonetheless, surfaces with emittance values near 0.95 also experience heightened heat loss, leading to a decrease in the exit temperature of the heat transfer fluid. To address this issue, "selective surfaces" have been engineered to exhibit a high absorptance for solar radiation and a low emittance for longwave radiation. It's important to note that such materials are not naturally occurring. These materials possess thermal radiation properties limited to just a few wavelengths of the relevant radiation. Solar radiation typically peaks at around 0.6 μm , while long-wave thermal radiation peaks at 9 to 10 μm . The peak intensity wavelength of emitted thermal radiation can be determined using Wien's law, as indicated in Equation 2.

$$\text{Wavelength } , \mu\text{m} = 2898/T \quad \text{Equation 2}$$

A layer that absorbs radiation A material that is only several μm thick will effectively absorb radiation with wavelengths around 0.6 μm while remaining almost invisible to longwave thermal radiation with wavelengths near 10 μm . The numerical equivalence of a material's thermal radiation emittance and absorptance at the same wavelength can be demonstrated through the application of the second law of thermodynamics. Hence, a sufficiently thin material absorbs minimal longwave thermal energy while emitting a similarly small amount. This principle is leveraged in the construction of solar collector composite panels, which consist of a thin layer of chrome oxide, nickel oxide, or aluminium oxide with nickel (2 – 3 μm), coupled with a polished copper or aluminium metal sheet. Typically, the surface coating is deposited galvanically, resulting in a surface that effectively absorbs solar energy while emitting only a negligible amount of thermal radiation [1].

According to [1], the useful thermal energy derived from a solar collector is determined by the disparity between the solar radiation transmitted through the glazing and absorbed as heat, and the heat dissipated to the surroundings represented by the governing equation, normalized to the absorber plate area.

$$q_u = (r\alpha)IA_{ap} - U_tA_{ap}(t_{ap} - t_a) = mc_p(t_o - t_i) \text{Equation 3}$$

where: q_u is useful heat gained, W

A_{ap} is area of the absorber plate, m^2

I is instantaneous direct normal solar irradiation, W.m^{-2}

m is transport fluid mass flow rate, kg. s⁻¹

c_p is specific heat of the transport fluid, J.kg⁻¹. K⁻¹

t_{ap} is average temperature of the absorber plate,

t_a is ambient temperature of air,

t_i is temperature of the fluid transporting the working fluid into the collector,

UL is thermal conductance of the collector, standardized to the absorber plate area., W.m⁻². K⁻¹

α is solar absorptance of the collector plate

r is solar transmittance of the collector glazing

The efficiency,⁵ of the power transmission is calculated based on Equation 2.4.

$$\eta = \frac{m c_p (t_{ap} - t_a)}{I A_p} \quad \text{Equation 4}$$

Because determining the temperature of the absorber plate in an actual installation poses challenges, the equations mentioned above are susceptible to some degree of error. Additionally, the absorber temperature is unlikely to be uniform, necessitating the calculation of an average temperature across the plate. ASHRAE recommends the use of an adjustment factor, known as the heat removal factor (FR), to allow the substitution of the inlet transport fluid temperature for the absorber plate temperature; the relationship between these factors are shown in Equations 5 and 6 [1].

$$q_u = FR (r\alpha) I A_p - FR UL A_p (t_i - t_a) \quad \text{Equation 5}$$

$$\eta = \frac{FR (r\alpha) I A_p - FR UL A_p (t_i - t_a)}{I A_p} \quad \text{Equation 6}$$

The adjustment can be conceptualized as the ratio between the net heat collected and the net heat that would be collected if the collector absorber plate had a uniform temperature, denoted as t_i . Typically, when compared to double-glazed collectors, single-glazed collectors allow more solar radiation transmission to the absorber plate, but they are less effective in insulating against heat loss to the environment. Figure 4 shows a cut-away picture of a typical flat plate collector.

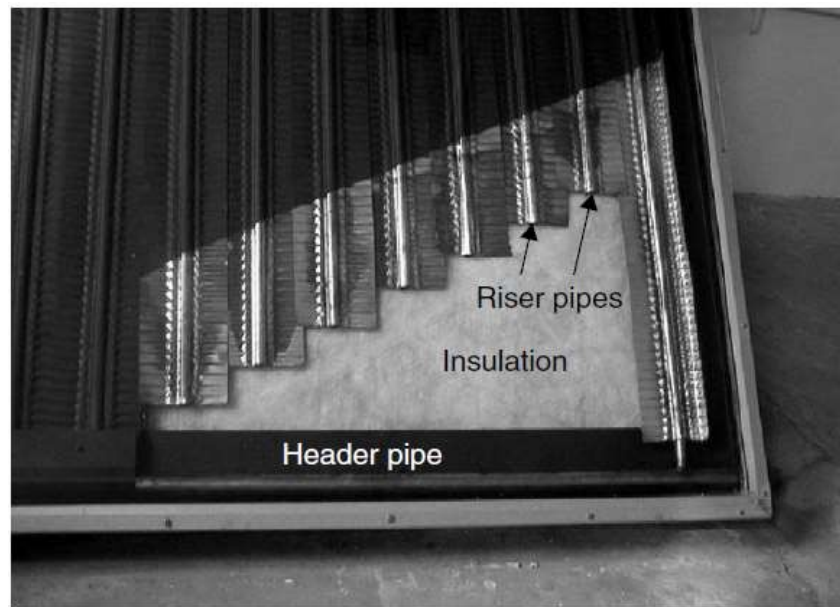


Figure 4: Cut-away view of a flat plate collector [4]

The flat plate collector has low heat flux through the plate as one of its main problems; this reduces the thermal efficiency of the dryer [3].

The CPCs are non-imaging concentrators. They can reflect to the absorber all of the incident radiation within wide limits. When two parabola sections are placed facing each other, the necessity of moving the concentrator to track the sun is reduced. Through multiple internal reflections, any radiation entering the aperture within the collector's "acceptance angle" is directed towards the absorber surface positioned at the bottom of the collector. Figure 5 shows various configurations of the collector. The compound parabolic reflectors are required to have a gap between the receiver and the reflector in order to prevent the reflector from acting as a fin; thus, conducting the heat away from the absorber. However, it is important to maintain a small gap, as a larger gap leads to a loss of reflector area and consequently results in performance degradation [4].

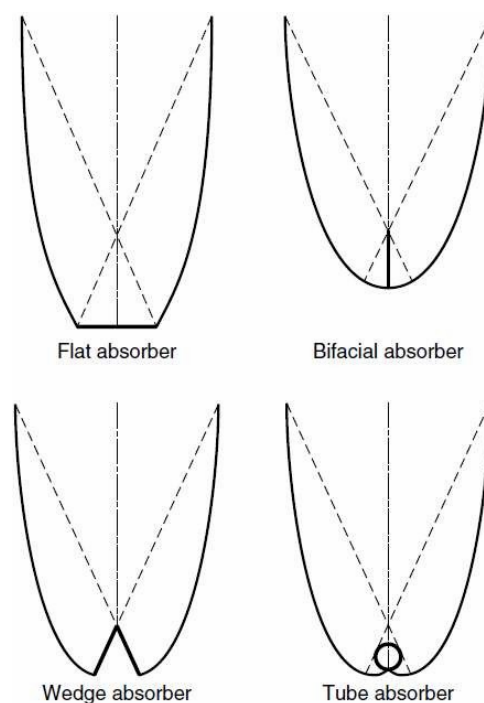


Figure 5: Absorber types of CPCs [4]

Involute reflectors can also be used in CPCs (Figure 6). In practice, the CPCs are arranged in an array with absorbers connected to facilitate the transfer of fluid across the panels to and from the utility chamber (Figure 7).

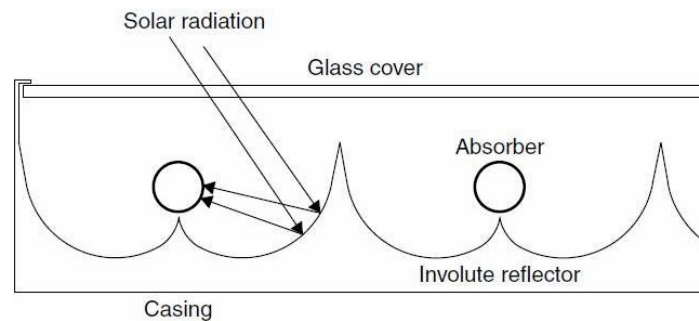


Figure 6: Schematic diagram of CPC [4]



Figure 7: Field installation of CPC panels [4]

Solar collectors employ arrays of one or two concentric glass tubes, connected in parallel and enclosed within a protective structure, forming evacuated tubes. These tubes, akin to the shape and size of fluorescent bulbs, are designed to prevent convective heat loss from the absorber. The efficiency of these collectors exceeds that of conventional flat-plate solar collectors, and they typically achieve higher collection temperatures, often surpassing 50 °C. The elevated temperatures attained by these collectors enable practical applications for process heat in commercial settings and facilitate the use of absorption refrigeration systems for solar air conditioning [1].

Evacuated-tube collectors find application in domestic hot water supply and are particularly well-suited for very cold regions where flat plate solar collectors exhibit reduced efficiency. The evacuated tube design effectively minimizes heat loss from the absorber plate. However, the enhanced thermal insulation in evacuated tube solar collectors slows down the rate of snow melt from the collector panel, leading to reduced collection efficiency on snowy days. The basic design of this collector type illustrated in Figure 8, features a flat or curved metal plate (typically aluminium) with a selective surface enclosed within an evacuated glass tube. A challenge associated with this design is ensuring a proper seal between the glass and metal at the ends due to differences in the rate of thermal expansion. Figure 9 showcases the practical application of this type of solar collector in the field [1].

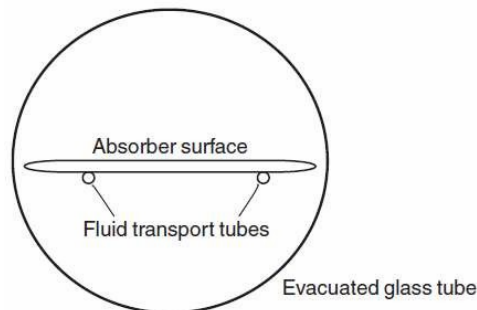


Figure 8: Sectional view of the evacuated-tube solar collector [1]

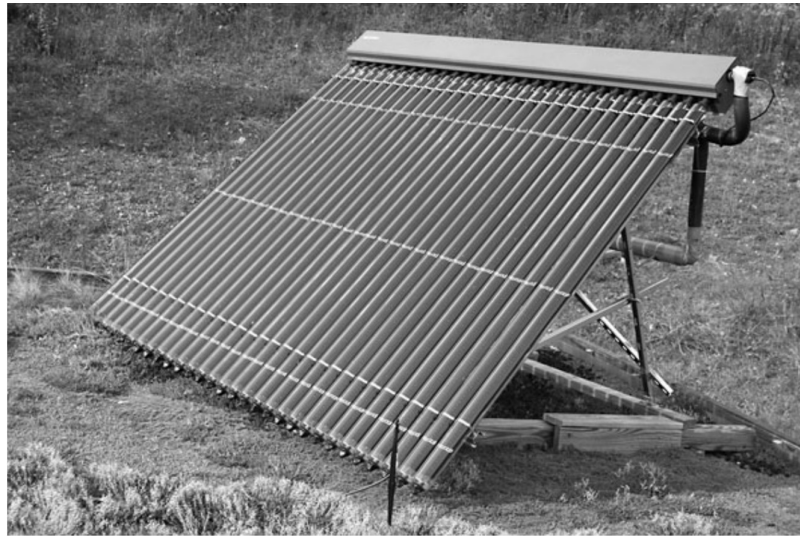


Figure 9: Field installation of the evacuated-tube solar collector [1]

[1] noted that the temperatures possible with flat-plate type solar collectors are below the boiling point of water – even with specially designed surfaces. This is not the case with concentrating solar collectors. These types of collectors provide large amounts of heat that can be used in absorption chilling, food processing, solar air conditioning, and electricity generation – based on the Brayton, Rankine or Stirling power cycles. Concentrating solar collectors are designed in form of parabolic troughs, dish, non-imaging concentrators or central receiver. Parabolic collectors work based on the principle that light rays parallel to the axis of a parabolic surface reflect to a single focal point (Figure 10). The focal line is where a pipe carrying a heat transport fluid is located in a two-dimensional trough. Temperatures in this design are commonly 300 °C. If the incident solar radiation changes direction, the focal line remains unchanged. This configuration offers a significant advantage as solar tracking is simplified with only a single degree of freedom involved, where the trough can pivot back and forth to maintain the focal line. However, as the degree of obliqueness increases, the total solar power collected decreases proportional to the cosine of the angle away from perpendicular [1].

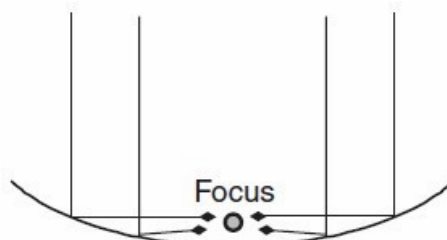


Figure 10: Working principle of the parabolic trough solar collector [1]

The material used in making the parabolic trough affects the thermal performance of the solar collector. [5] investigated the thermal performance of a parabolic trough solar collector produced using aluminium and stainless steel. Their findings showed that besides being cheaper, aluminium was 20% more thermally efficient than stainless steel.

In non-imaging solar concentrators, solar energy entering the collector's aperture undergoes

multiple reflections towards the bottom, where an absorber plate extracts thermal energy. While the solar concentration is less intense compared to parabolic trough designs, the precision of focus is not as critical, and precise sun tracking is not required. Consequently, this type of collector can elevate the operating temperature of the working fluid at a lower cost. In simpler designs, the collector's sides are constructed with straight and reflective surfaces, directing a significant portion of the incoming sunlight to the absorber plate. The temperature generated in such non-imaging solar concentrators is adequate for applications in heating and even power generation. Figure 11 illustrates the working principle of a non-imaging solar collector [1].

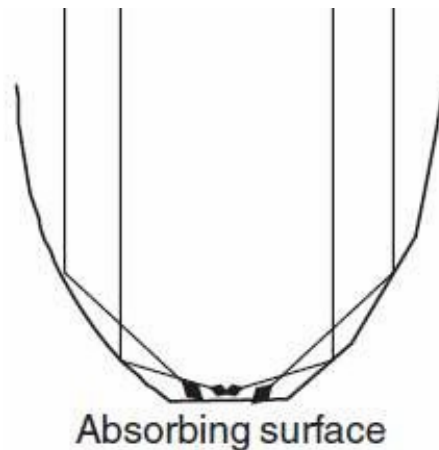


Figure 11: Working principle of the non-imaging solar collector [1]

Parabolic dish collectors focus solar energy on a single point (Figure 12). This results in highest operating temperature of all solar collectors. Theoretically, at the focal point of a dish-shaped concentrating collector, the temperature has the potential to reach the surface temperature of the sun. However, in practical applications, the maximum operating temperature typically reaches around 2000 °C. The tracking system for such collectors is more sophisticated, requiring two degrees of freedom to accurately orient it and capture maximum solar power throughout the day. The complexity of solar tracking has, however, restricted the widespread application of dish concentrators, confining their usage mainly to research and development projects [1].

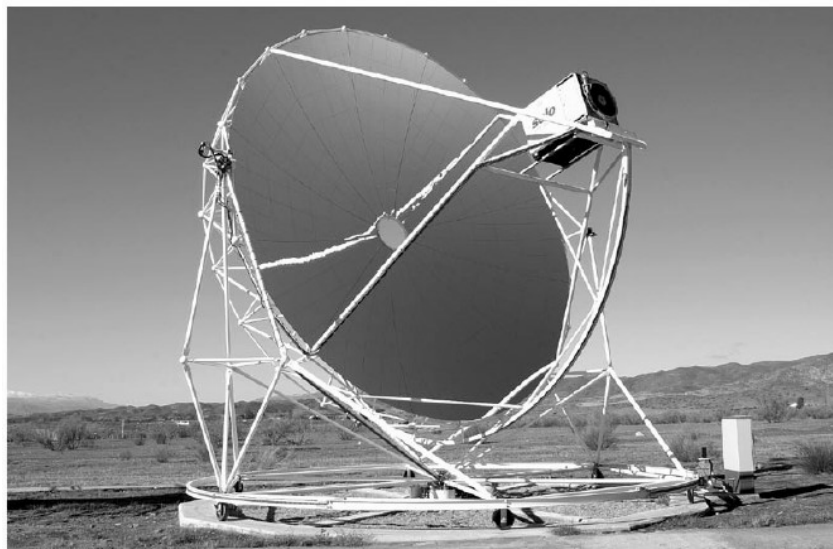


Figure 12: Parabolic dish collector [4]

Thermodynamic cycles used to power heat engines, such as the Rankine and Brayton cycles, require higher source temperatures to work more efficiently. While concentrating solar collectors can achieve high temperatures, the practicality of manufacturing sufficiently large parabolic dishes or troughs for practical power generation remains a challenge. As a solution, large fields of individually computer-controlled mirrors, known as "heliostats," are employed to concentrate reflected solar energy onto a stationary solar receiver mounted on a high tower. The absorbed power is then utilized to heat the working fluid that drives a steam boiler or to heat air in a Brayton Cycle. These systems can generate temperatures at the focus well above 1000 °C. The mirrors are precisely controlled with two degrees of freedom to track the sun's movement. Although they capital costs

of central receivers are high, they are effective and developments in technology is expected to reduce the costs. Besides its application in power generation, central receivers can be used in solar furnace as shown in Figures 13 and 14.



Figure 13: Detail of a heliostat [4]

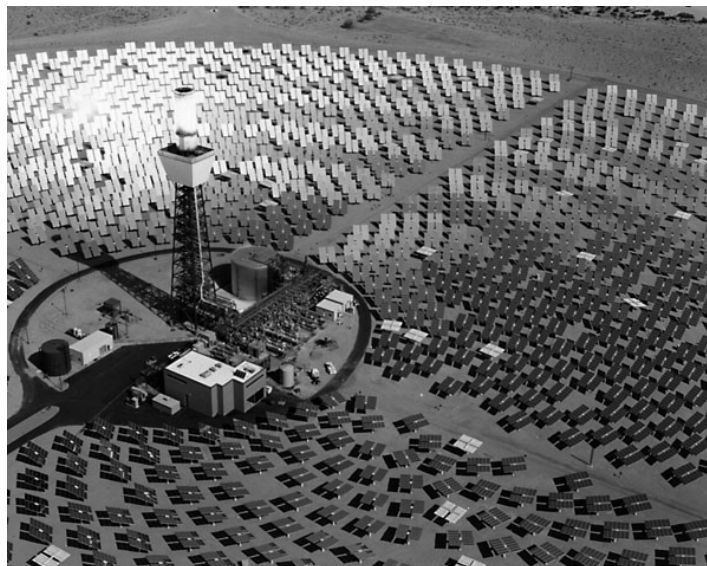


Figure 14: Solar one solar furnace in Barstow, California Source[1]

Table 1 presents a summary of solar collectors and their operating temperature range as well as the control.

Table 1: Solar energy collectors

Motion	Collector Type	Absorber Type	Concentration Ratio	Indicative Temperature Range (°C)
Stationary	Flat-plate collector (FPC)	Flat	1	30 – 80
	Evacuated tube collector (ETC)	Flat	1	50 – 200
	Compound parabolic collector (CPC)	Tubular	1 – 5	60 – 240
Single-axis tracking	Compound parabolic collector (CPC)	Tubular	5 – 15	60 – 300
	Linear Frensel reflector (LFR)	Tubular	10 – 40	60 – 250
	Cylindrical trough collector (CTC)	Tubular	15 – 50	60 – 300
	Parabolic trough collector (PTC) Parabolic dish	Tubular Point	10 – 85	60 – 400

Two-axis tracking	reflector (PDR) Heliostat field collector (HFC)	Point	600 – 2000 300 – 1500	100 – 1500 150 – 2000
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Note: Concentration ratio is the aperture area divided by the receiver/absorber area of the collector

[4]

Food dehydrators (commonly known as dryers) are equipment that are used to remove moisture from food items such as fruits and vegetables. They use low temperatures (mostly $< 60^\circ\text{C}$) to facilitate the removal of moisture from foods slowly. The sources of heat for dehydrators include electricity, solar and geothermal power (Mitchel, 2021; Ritcher, 2021). A food item is said to be “dried” when any amount of moisture is removed from it; but when it is “dehydrated”, it implies that more than 95% of moisture in it is removed. The purpose of dehydrating food is to prevent food from spoiling by increasing its shelf life. Oxygen, heat, moisture, light and microorganisms such as moulds, bacteria and fungi are the main degrading agents to food. Dehydration creates an inhabitable environment for most organisms [6]

According to [1], food processing leads to loss of nutrients to some degree. Dehydration involves subjecting food to a slightly elevated temperature for an extended duration, which is ideal for maximizing the retention of nutrients. Studies published by the United States Department of Agriculture indicate that approximately 40 to 60% of nutrients are lost when food is stored by freezing. In canning, nutrient loss ranges from 60 to 80%, while food dehydration results in an average nutrient loss of only 3 to 5%. Freezing temperatures and the high temperatures associated with canning can lead to the rupture and release of nutrients in fruits, vegetables, and greens. In contrast, dehydration does not induce such changes.

Dehydration using solar power is one of the oldest and commonest forms of drying. Traditionally, this form of drying involves spreading the item for several hours (or days) to be dried in the sun. Drying is achieved by solar radiation, ambient temperature, relative humidity of ambient air and natural wind. Solar dryers use air collectors to capture solar energy. They are used primarily by the agricultural industry to reduce moisture content of food materials to a level that prevents its deterioration. The main processes involved in drying include transfer of energy from the heating source to the product and another is the mass transfer of moisture from the interior of the product to its surface and from the surface to the surrounding air [4].

Although the natural (open-sun) drying is cost effective (no capital investment is required) and widely used, there are some limitations to its use. The obvious limitations are contaminations from dust, dirt, atmospheric pollution, and animal attacks. Solar dryers are used to supply more heat to a product than is available naturally under ambient conditions; thus, increasing the vapour pressure of the crop moisture to sufficient amounts. It also significantly reduces the relative humidity of the drying air; thereby increasing its moisture-carrying capability. This in turn ensures a sufficiently low equilibrium moisture content [4]. Furthermore, study by [7] showed that locally fabricated solar dehydrator (Figure 15) removed more moisture content from vegetables than natural (direct sun) drying. In a similar study, [8] analysed the thermal performance of a solar food dehydrator (Figure 16). Results obtained showed that the dehydrator produces dried food stuff with superior colour, aroma and taste than ambient temperature drying.



Figure 15: Locally fabricated solar dehydrator [8]



Figure 16: Locally solar dehydrator [8]

[9] designed and fabricated a solar food dehydrator for root crops and vegetable drying using locally available materials (Figure 17). Their study showed that products dried in a dehydrator are less susceptible to damage by rain or pest compared with open sun drying. Their design could be used for drying food items such as yams, cassava, maize and plantain. In terms of capital expenses, the cost of producing the dehydrator was lower than would be required to produce a mechanical dryer.



Figure 17: Locally solar dehydrator for root crops and vegetables [9]

Solar dryers may use solar energy as the primary heat source or as supplementary source of heat. The airflow can be natural draft or forced convection using a fan. The product is dried by exposing it to flow of heated air, by exposing the product directly to solar radiation or a combination of both. Heat transfer occurs by convection (from the flowing air), by direct radiation from the sun and by conduction from heated surfaces in contact with the product. Absorption of heat by the product causes moisture to diffuse from the interior of the product to its surface. The rate at which this occurs depends on the moisture content of the product. The surface water on the product is displaced by evaporation. If the rate of diffusion is slow, it becomes the limiting factor in the drying process, on the other hand, if it is fast enough, the controlling factor is the rate of evaporation from the surface [4].

Solar dryers that have the product directly exposed to incident radiation result in heat being absorbed inside the material; thus, raising its internal and surface temperatures. The rate at which this occurs is determined by solar absorptance of the product. To ensure acceptable product quality, the rate of heat transfer and evaporation must be closely controlled to ensure both optimum drying rates and product quality. Maximum drying rate is required so that drying is economically viable. Solar dryers are classified based on the heating mode employed (active or passive), the manner in which the heat is utilized and their structural arrangement

(distributed, integral or mixed mode).

In active solar drying systems, a fan is employed to circulate air through the air collector to the product. On the other hand, in passive (natural circulation) systems, heat transfer across the product occurs through buoyancy forces induced by wind pressure, buoyancy forces (as a result of wind pressure) causes heat transfer across the product. In active systems, external power source is required to power the fans or provide auxiliary heating ([5],[4].

In distributed-type solar dryers, the solar energy collector and drying chamber are distinct units. In contrast, in integral-type solar dryers, a single apparatus serves both for solar energy collection and drying. This means that the chamber responsible for collecting solar energy is also utilized to house the materials undergoing the drying process. The integral-type design has a major setback: the material being dried can be damaged by excessive localized heat and caramelization (i.e. formation of sugar crystals on the crop surface). Thus, indirect drying is required for perishables and fruits in which the vitamin content of the dried product can be reduced by direct exposure to sunlight. The mixed mode dryer is similar to the distributed type of dryer, but the walls and roof of the dryer are made from glass to allow direct solar heating. Unlike conventional dryers, the maximum drying temperature in solar dryers is determined by the solar collectors; This is attributed to the fact that the efficiency of these dryers tends to decline at higher operating temperatures, posing a challenge for achieving an optimal design [4]. Figures 18, 19, 20, 21, 2. and 23 show schematics of various types of dryers.

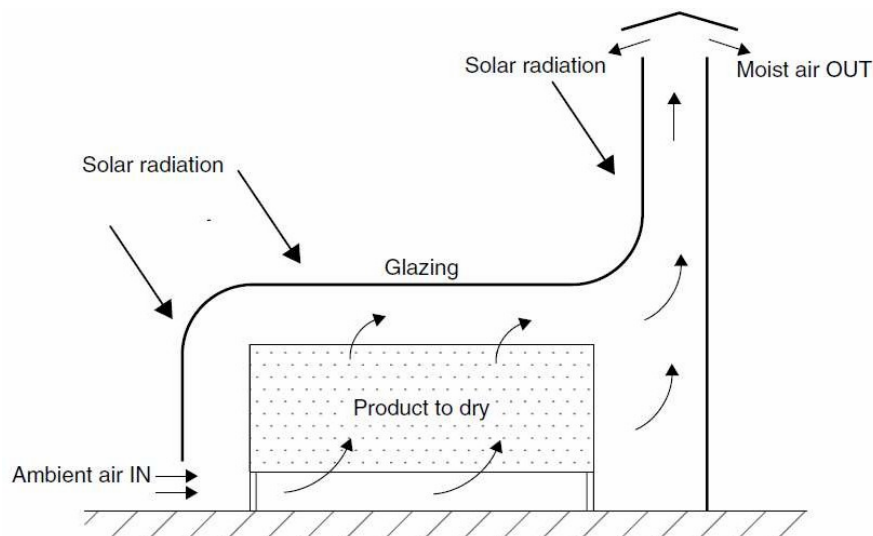


Figure 18: Schematic diagram of an integral-type passive solar dryer Source[4]

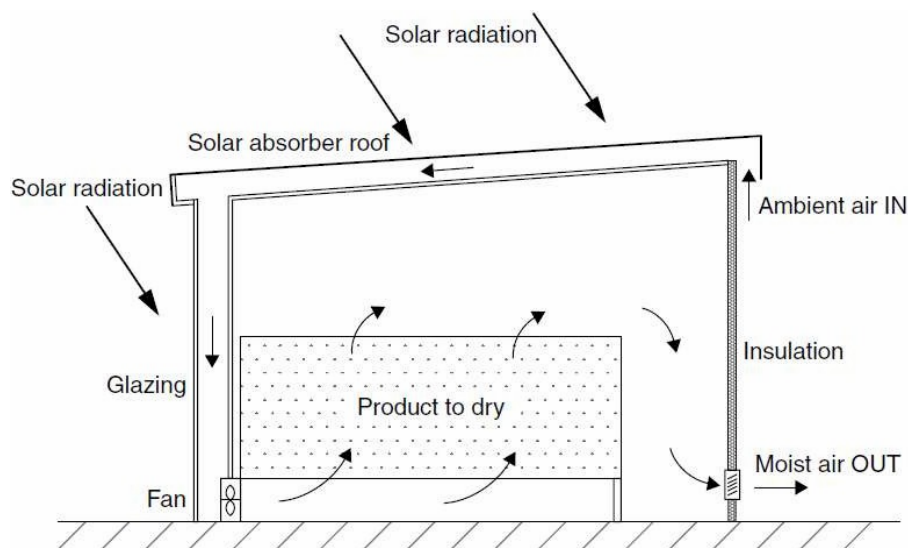


Figure 19: Schematic diagram of an active collector-roof solar energy storage dryer [4]

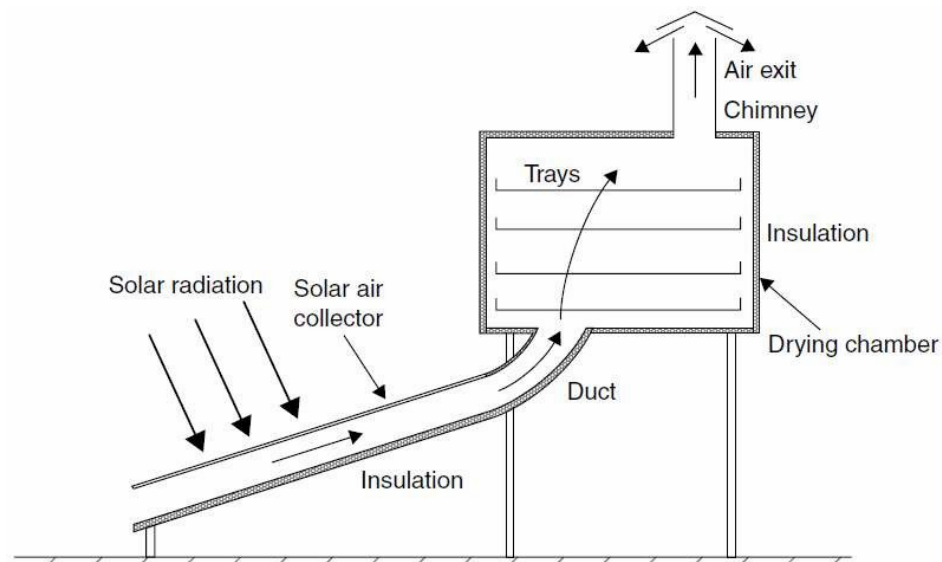


Figure 20: Schematic diagram of a distributed-type passive solar dryer Source: [4]

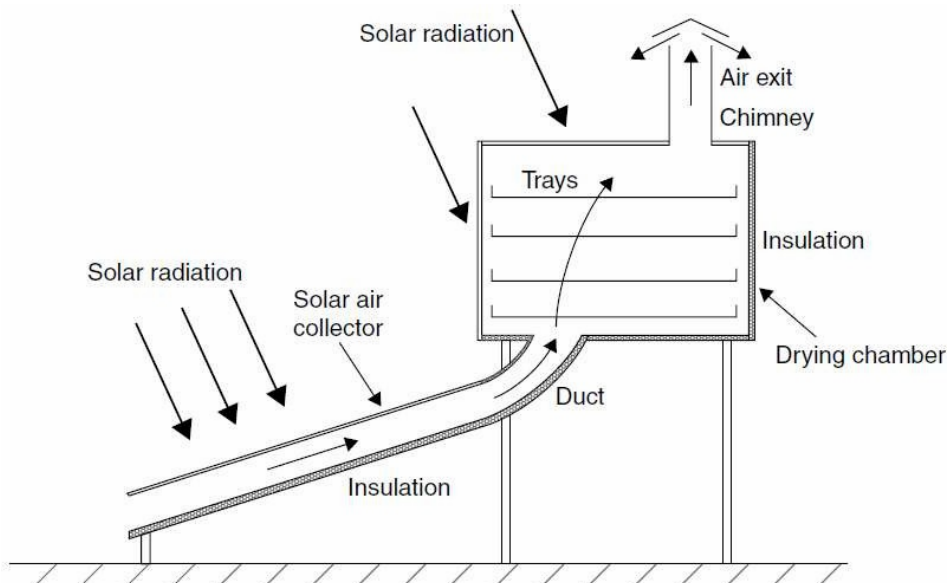


Figure 21: Schematic diagram of a natural circulation, mixed-mode solar energy dryer[4]

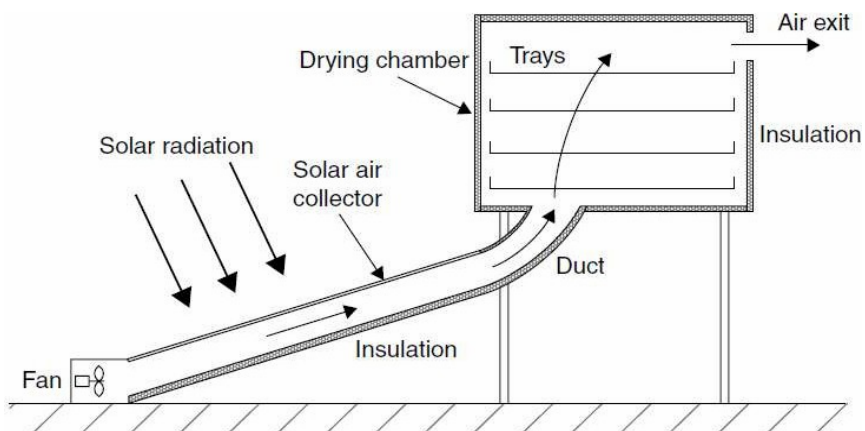


Figure 22: Schematic diagram of a distributed-type active solar dryer Source [4]

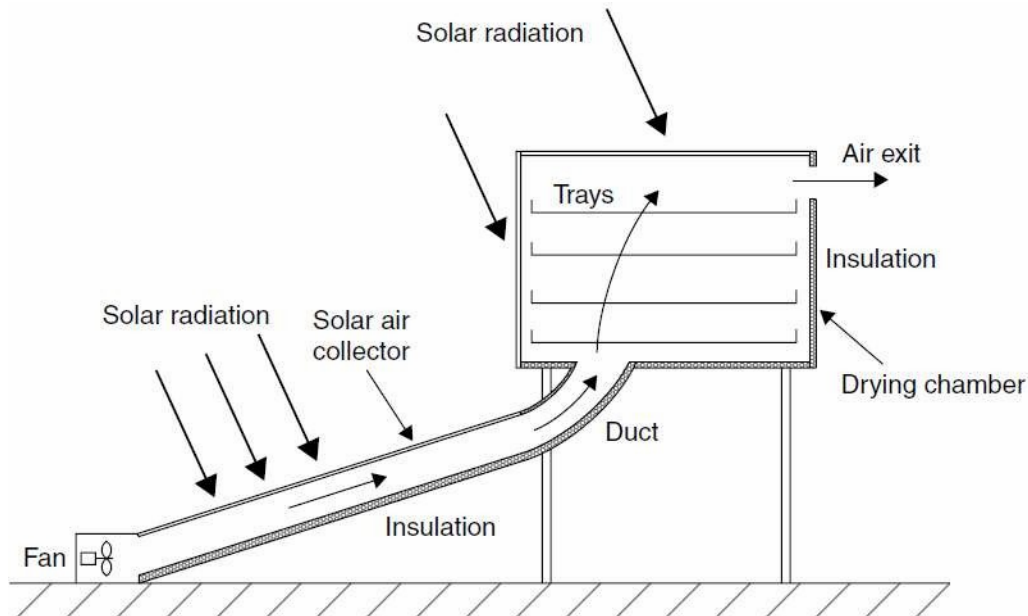


Figure 23: Schematic diagram of a mixed-mode active solar dryer Source [4]

[10] notes that airflow in food dehydrators can be vertical or horizontal. The horizontal airflow cabinet dehydrators are often larger and are used for large capacity dehydration in comparison with the vertical (stackable) dehydrators. Table 2 shows a comparison between horizontal and vertical airflow food dehydrators.

Table 2 Comparison between vertical and horizontal food dehydrators		
S/N	Vertical Air flow Food Dehydrators	Horizontal Food Dehydrators
1	Airflow originates from the bottom to the top of the dehydrator	Air flows from the rear of the dehydrator to the front.
2	Mostly stackable	Not stackable
3	Tend to dry food on the lower trays faster than on the upper trays	Uniform drying of food items
4	Food flavours may be mixed as air passes from one level of food to another	No contamination in flavours
5	Base mounted fan-heater configuration can be polluted by food particles	Less vulnerable to problems caused by food ingress to the fan-heater unit
6	Difficult to load and offload the trays	Easy loading and offloading of the trays

The positioning of the fan in a dehydrator plays a crucial role in effective dehydration, as highlighted by [6]. The optimal placement for fans in a dehydrator is at the back wall, generating a consistent airflow that moves horizontally across each food shelf. This design facilitates the expulsion of moisture out of the front and sides of the dehydrator. In contrast, some dehydrator designs feature fans located at the bottom or top, forcing air vertically through each layer of food. However, this arrangement leads to inadequate air circulation, as food layers obstruct the airflow. Consequently, the trays closest to the fan dry first, while those higher up may retain moisture.

Another key feature of food dehydrator is temperature control. This is very important because different food items have different temperatures to be dehydrated properly. Hence, if there is no precise control of temperature in the dehydrator, it cannot dehydrate effectively. For this reason, dehydrators should not be interchangeable with ovens. The later typically operates at much higher temperatures. Conventional convection ovens have lowest temperature setting of about 65 °C - way too high for many food items [10].

[2] carried out numerical analysis of the thermal performance of a solar dryer. In their research, studies on the

dryer were carried out using experimental, thermo- graphical and CFD techniques. CFD simulation was used to model the heat transfer variations and fluid flow. The study was validated using experimental and thermo-graphical data. They noted that thermocouple and data loggers – although commonly used in recording temperature in dryer analyses – they cannot be used to examine thermal properties of different points. To overcome the setback, they used an advanced thermal imaging technique: the thermo-graphical method to map the temperature at all points in the dryer. Such system requires no probe or contact with the dryer. They affirm that validation is very important in the modelling of drying processes; thus, although CFD simulation is one of the key analysis methods used in studying the heat variations and fluid flow across the dryer, the model must be verified using experimental data, before being adopted for practical use.

An improved solar fruit dryer was developed by [11]. Their design resulted in an increase in temperature of 10 more than conventional designs. This led to a considerable reduction in drying time (i.e. the time taken to reduce the moisture content to a desired level) of tomatoes by 27%.

[12] compared the performance of a double pass solar dryer (DPSD), solar cabinet dryer (SCD) and traditional open-sun drying (OSD) for red chili drying in Vietnam. Their result showed that the overall drying efficiencies were 24.04%, 11.52% and 8.03% for DPSD, SCD and OSD respectively. The DPSD also performed better at retaining colour and reducing Aflatoxin B1 formation compared to the other methods. Figure 24 shows an illustration of the DPSD.

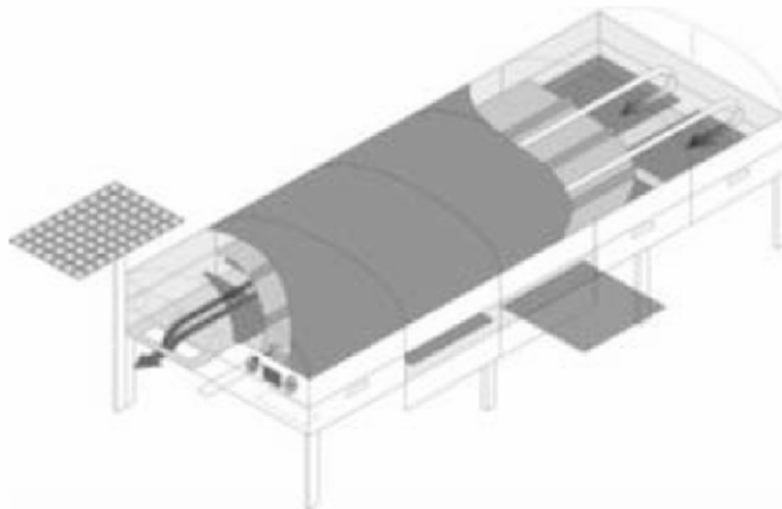


Figure 24: A double-pass solar dryer [12]

Focusing on the simulation and validation of the vanilla drying process in an indirect solar dryer prototype using Fluent CFD, it was observed that the temperature distribution within the solar collectors aligned well with experimental values, unlike the cabinet dryer. The disparity was attributed to the use of a fixed heat transfer coefficient in the cabinet dryer, as opposed to a flexible, time-dependent heat transfer coefficient. The researchers suggested that employing the latter (flexible heat transfer coefficient) would result in a more uniform temperature distribution inside the cabinet dryers.

[13] applied CFD in developing a fruit dryer. They developed seven different designs to study the air velocity profiles in a cabinet dryer with inlet air velocity of $3 \text{ m} \cdot \text{s}^{-1}$. Figure 25 shows various designs of the cabinet dryer; Figure 25 shows configuration of the cabinet dryer while Figure 26 shows the air flow distribution in different configurations of their solar dryer. Figure 27 shows the temperature distribution profiles in the dryer.

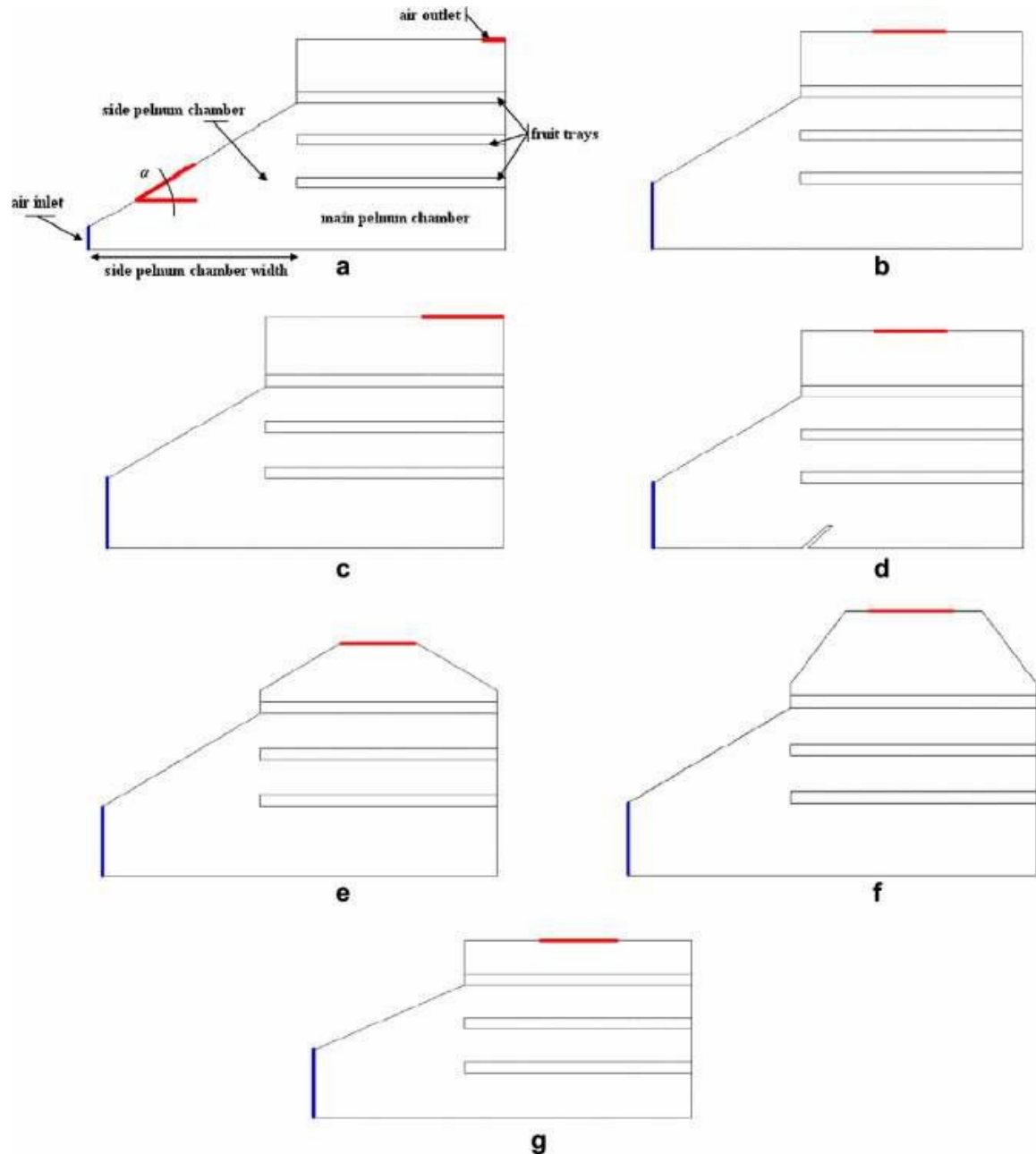


Figure 25: Various configurations of the cabinet dryer [13]

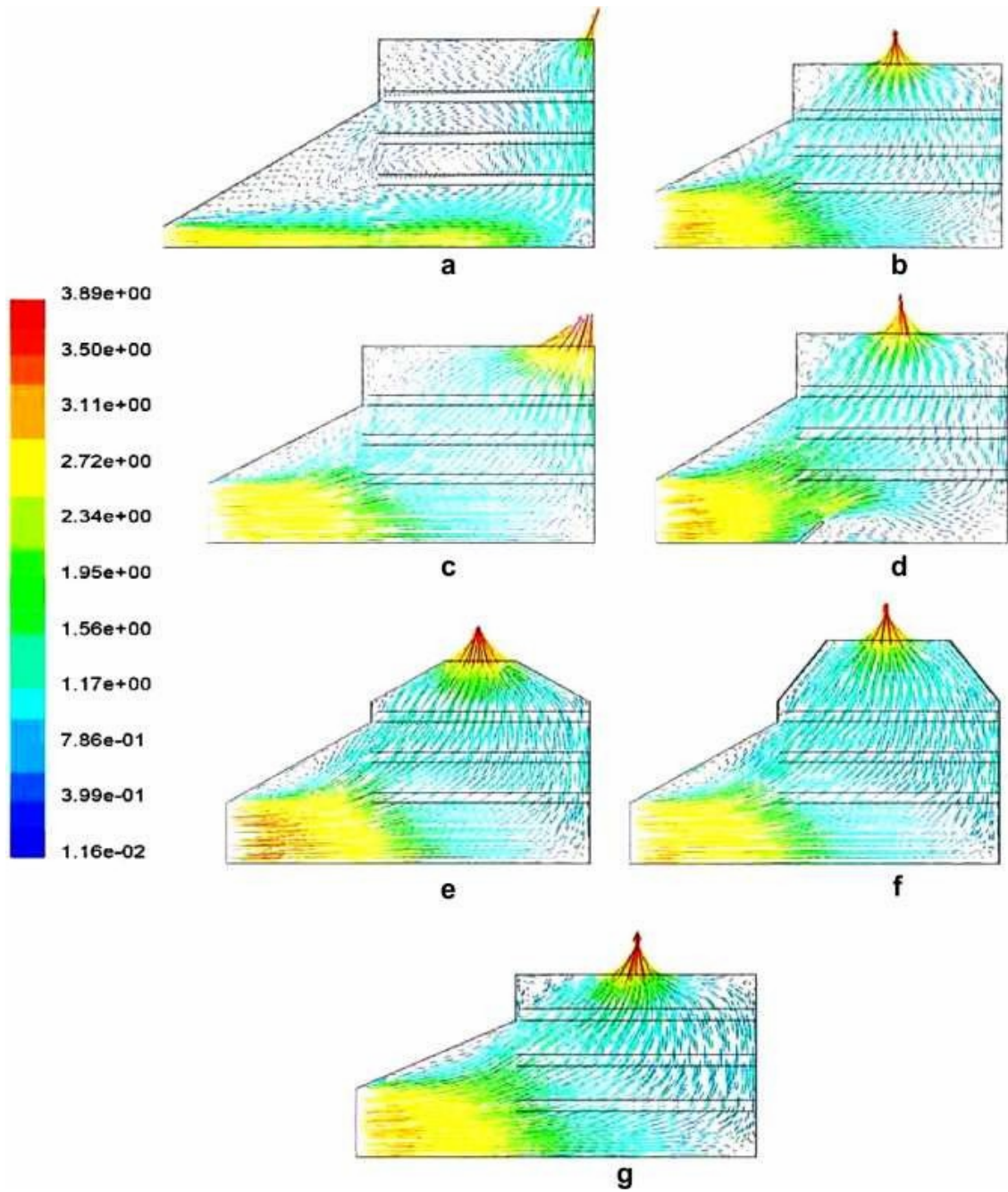


Figure 26: Configurations of a dryer showing velocity distribution of air flow distribution in the drying chamber [13]

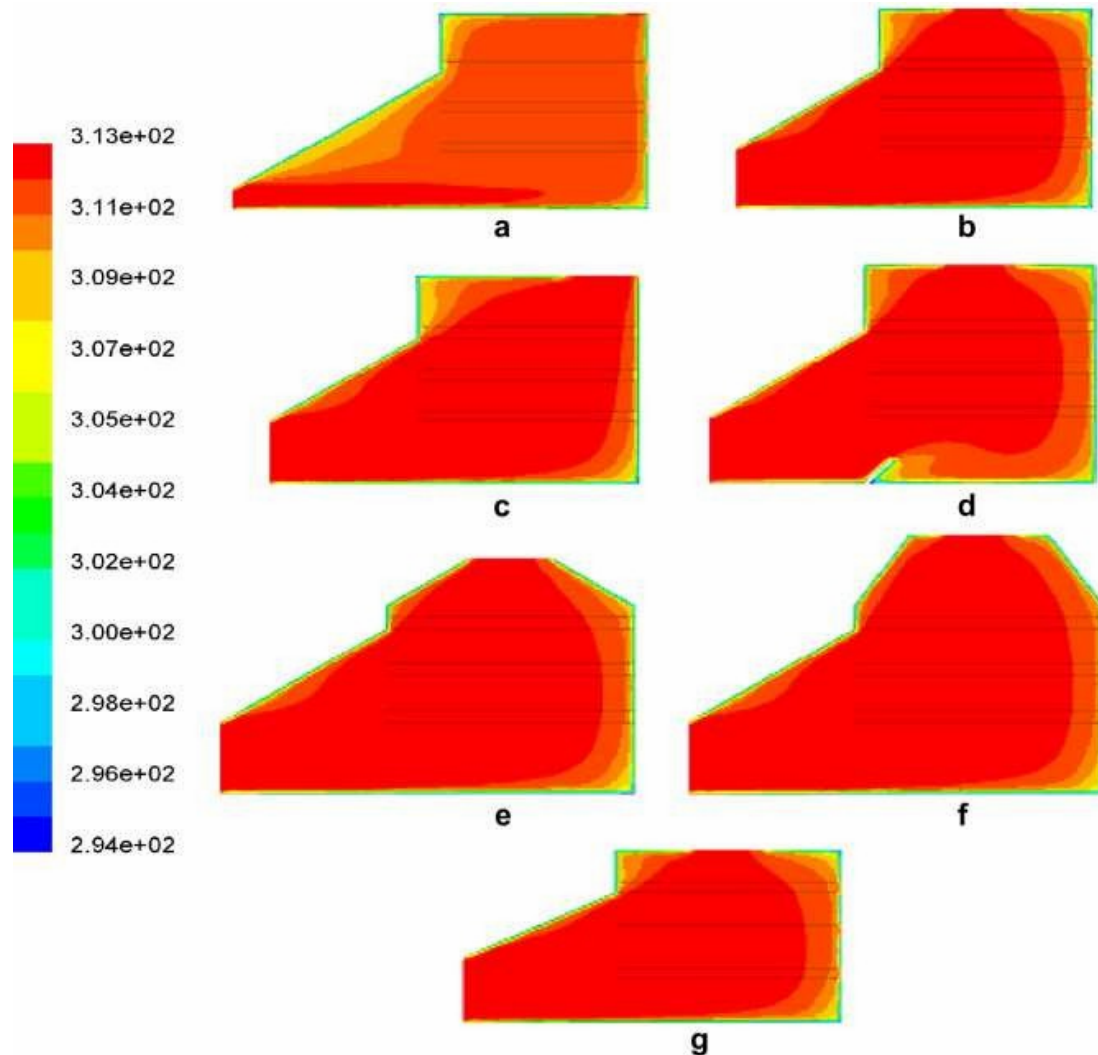


Figure 27: Drying air temperature distribution profiles for the seven designs; inlet air temperature = 313 K [13]

Their conclusion was that design (b) proved to be the most suitable for achieving uniform air temperature and velocity distributions within the drying chamber. The side mounted plenum chamber was also found to improve the conventional cabinet dryer's performance. Experimental data was gathered from eighteen (18) points in the drying chamber for both air temperature and velocity. The experimental result was compared to the CFD data for the design (b); the results were within acceptable range, with correlation coefficients of 99.9% for the drying air temperature and 86.5% for the air velocity in the drying chamber. Figure 28 shows a schematic of the experimental setup. The completed prototype is shown in Figure 29.

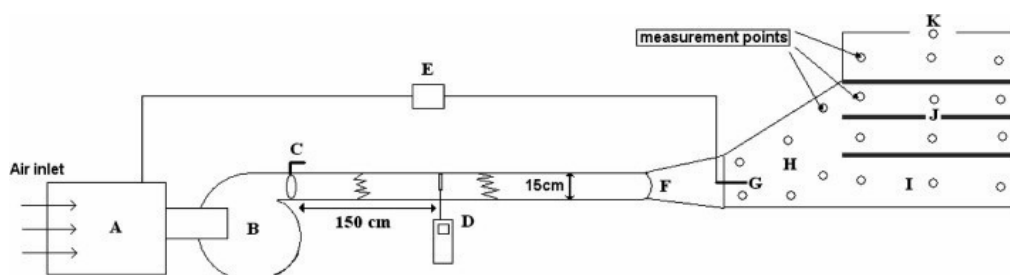


Figure 28: Schematic diagram of the cabinet dryer. (A) Electrical heating unit, (B) centrifugal fan, (C) damper, (D) hot wire anemometer, (E) thermostat, (F) diffuser, (G) thermostatic sensor, (H) side plenum chamber, (I) main plenum chamber, (J) fruit trays, and (K) air exist. [13]



Figure 29: Picture of the cabinet dryer [13]

A CFD analysis on greenhouse solar dryers was carried out by [14] based on free and forced convection processes. Their result showed that the maximum temperature and mass flow rate recorded in the forced convection system was 41% more than that obtained in the free (natural) convection process. The dryer model and simulation result are shown in Figure 30.

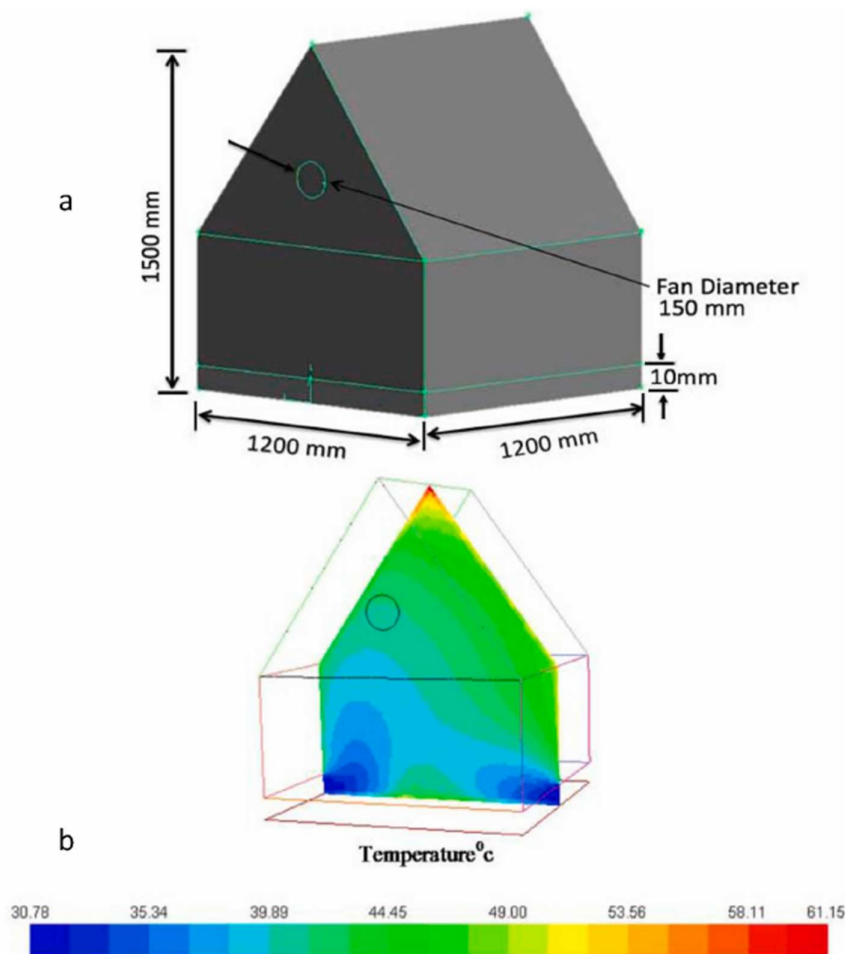


Figure 30: Model of the biomass dryer and CFD result [14]

[15] carried out modelling and CFD simulation of a solar cabinet dryer equipped with an evacuated tube solar collector (ETSC) and a Phase Change Material (PCM) thermal energy storage system. The findings from their study revealed that the use of Phase Change Material (PCM) resulted in a 1.72% and 5.12% increase in

input thermal energy for air flow rates of 0.025 kg/s and 0.05 kg/s, respectively. However, as the air flow rate continued to increase, there was a subsequent decrease in thermal energy input. Additionally, at the midpoint of the cabinet dryer, a maximum drying temperature of 70 °C was recorded. Figure 31 shows a 3D model of the experimental setup. Figure 32 shows the CFD simulation results.

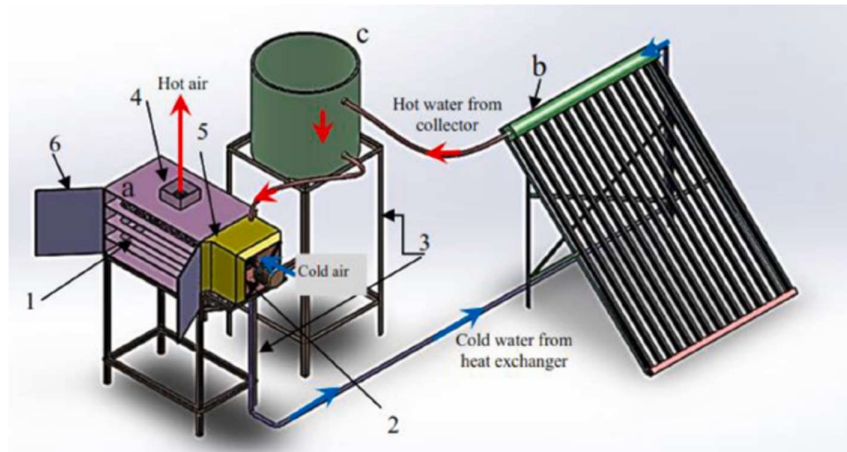


Figure 31: 3D model of the solar dryer with PCM (a) Dryer: 1- sample trays and cabinet, 2- fan, 3- chassis, 4- exhaust channel, 5- Heat exchanger, 6- doors; (b) ETSC; (c) Storage tank and PCM container inside [15]

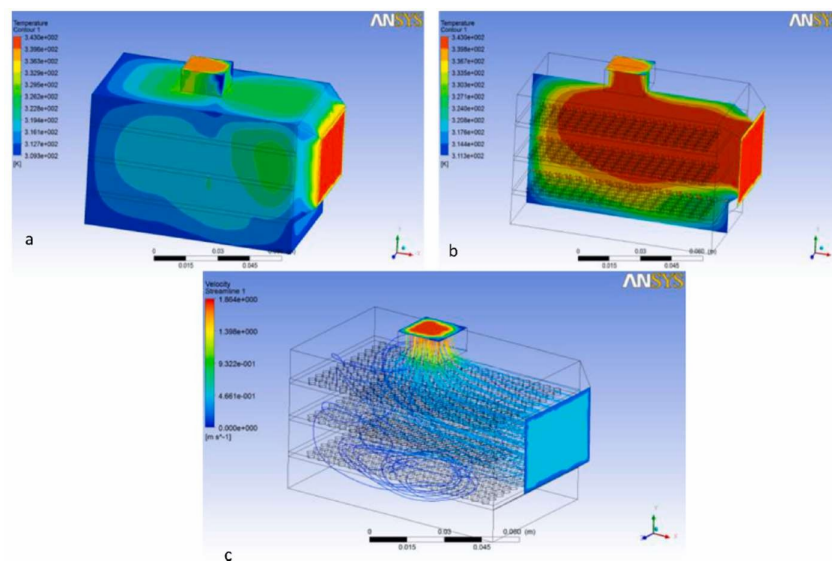


Figure 32: CFD Result of the solar dryer with PCM (a) the wall (b) midplane and (c) velocity streamlines of the cabinet dryer for airflow rate of 0.025 kg. s-1 [15]

[16] a solar cabinet chili dryer model was developed and analysed using Computational Fluid Dynamics (CFD). The dryer incorporated a double-pass solar collector, and the drying chamber was designed to achieve a uniform distribution of air velocity. A maximum of 39 °C was obtained in the drying chamber. Figure 32 shows air velocity distribution in the drying system.

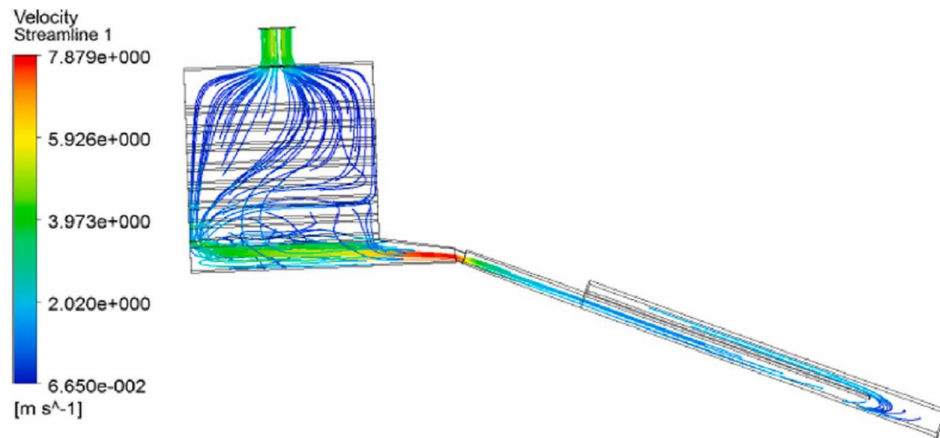


Figure 33: Air velocity distribution in the chilli dryer [3]

[17] carried out research on the simulation of mixed-mode solar dryer that has a vertical air distribution channel. They note that the final quality of a dried product depends significantly on the flow behaviour of the drying air. Using CFD, they investigated the transient distribution of different drying air parameters across a mixed-mode solar dryer. Their result showed that using a vertical air distribution channel can improve the homogeneity of drying air in a mixed-mode solar dryer. Their results in comparison with experimental data showed reasonable level of conformity. Figures 34 and 35 show a schematic diagram of the mixed-mode dryer and the CFD result respectively.

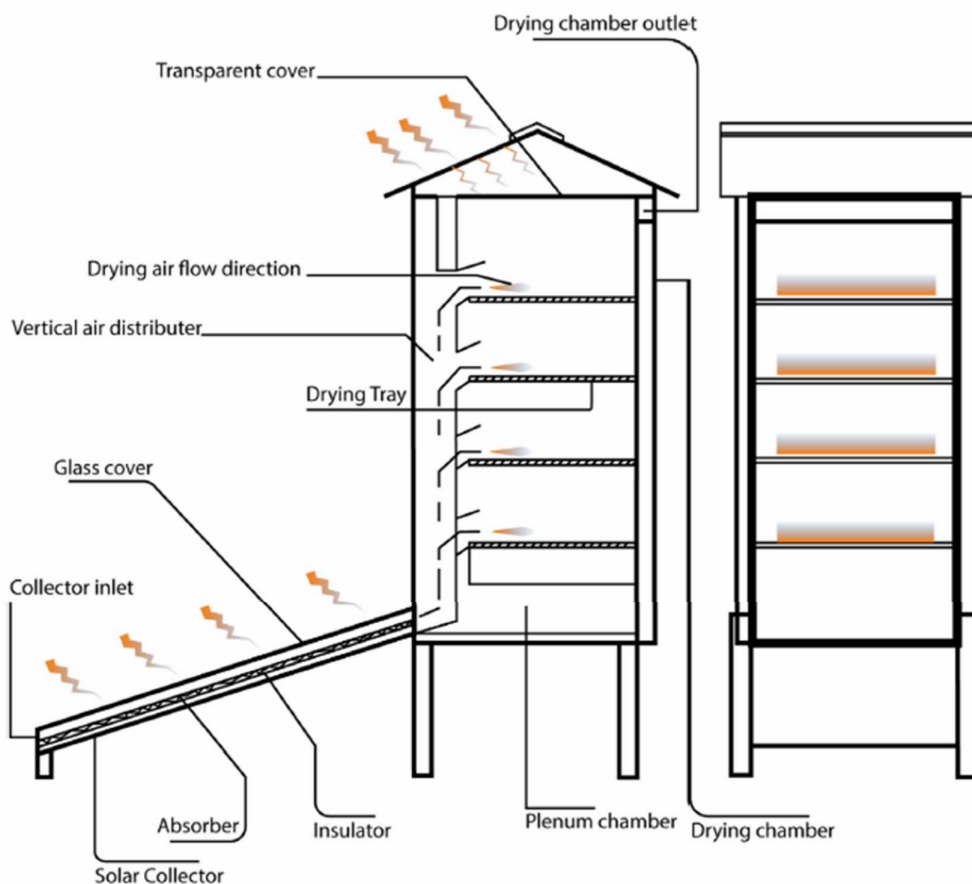


Figure 34: Schematic diagram of the mixed-mode dryer [17]

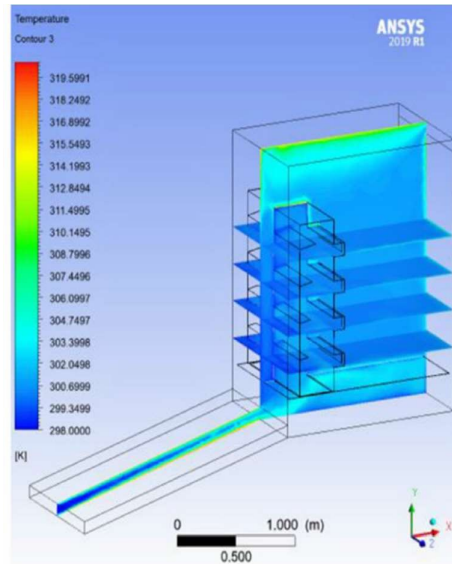


Figure 35: Temperature distribution through the dryer [17]

[18] studied the air distribution in a conventional tray dryer using CFD. The conventional tray dryer picture and its schematic is shown in Figure 36. They modified the geometry of the bottom of the tray dryer and subjected it to CFD analysis using CFDRC V2004 software. Figure 37 shows the velocity and vorticity CFD simulation of the conventional dryer.

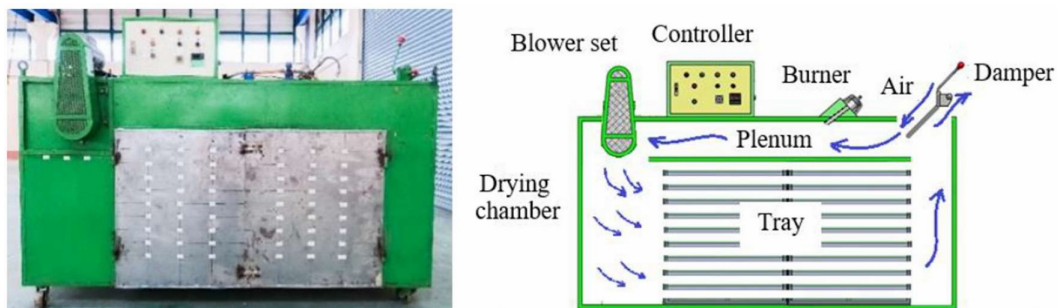


Figure 36: Conventional tray dryer [18]

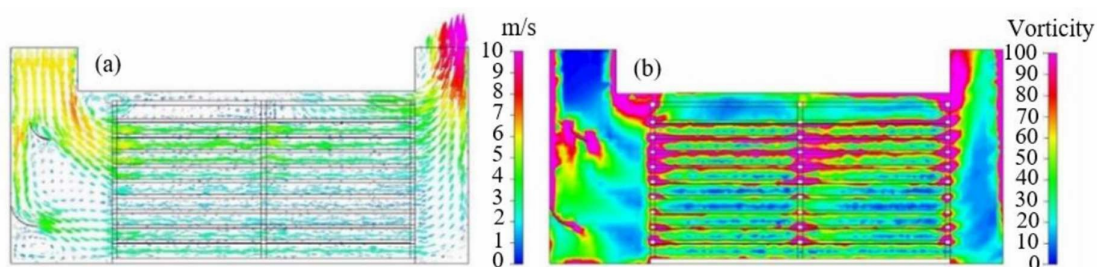


Figure 37: Velocity distribution and vorticity of air in the conventional tray dryer [18]

Their investigation involved six different designs. Figure 38 shows the flow distribution in the modified versions of the tray dryer. The air vorticity simulation result is shown in Figure 39. Case F shows better flow distribution and lesser vorticity at the corners of the drying chamber.

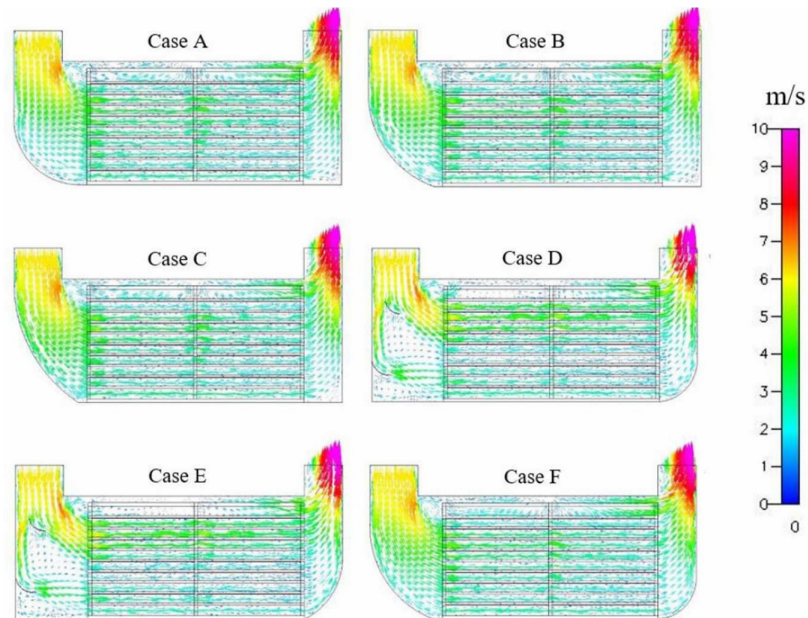


Figure 38: Velocity distribution of air in the modified designs of the tray dryer [18]

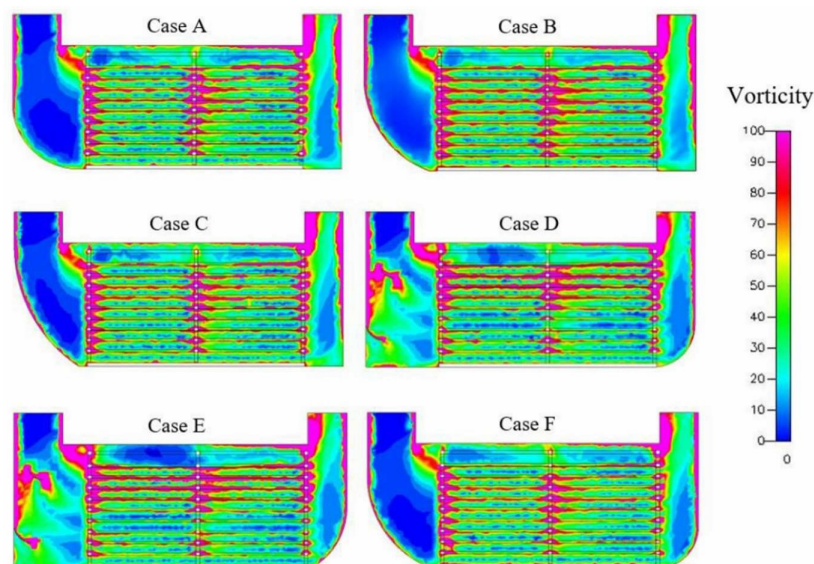


Figure 39: Vorticity distribution of air in the modified designs of the tray dryer [18]

The analysis for food drying analytically is a complex process. Drying can be characterized as a combined multiscale, Multiphysics problem. CFD modelling and simulation is very important in the study of solar dryers. However, very few studies have been conducted in this aspect. Also, studies have been conducted immensely on CFD modelling and simulation of fruits and vegetables at a micro level, without considering actual performance of the solar dryer. However, the performance of a solar dryer has immense impacts on the quality of the food item being dried [16]. [16] notes that, in solar dryers, the quality of dried food is influenced by various factors such as the type of dryer, temperature, humidity, and the distribution of pressure and velocity at each position within the drying compartment.

[16] investigated factors influencing the performance of solar drying equipment, focusing on drying rate, drying time, and product quality. The findings underscored the importance of maintaining uniform drying air velocity, optimal temperature, minimizing drying time, and ensuring even moisture distribution of the product within the drying chamber for efficient solar dryer operation. To ensure both safety and high product quality, Computational Fluid Dynamics (CFD) models, employed for performance evaluation or optimization studies of solar dryers, should have the capability to predict product quality alongside analyzing heat, airflow, and moisture transfer characteristics. Various computer software tools for dryer modeling and simulation utilize different discretization techniques such as finite element, finite volume, and finite difference. Such programs include ANSYS, COMSOL, Flow 3D, OpenFOAM and STAR CCM.

CFD involves the use of numerical methods and computer algorithms to analyse and solve problems involving fluid flows. It provides insight into flow patterns that are expensive, difficult or virtually impossible to study using traditional (experimental) techniques, such as wind tunnel studies. The procedure for CFD analysis is shown in Figure 40.

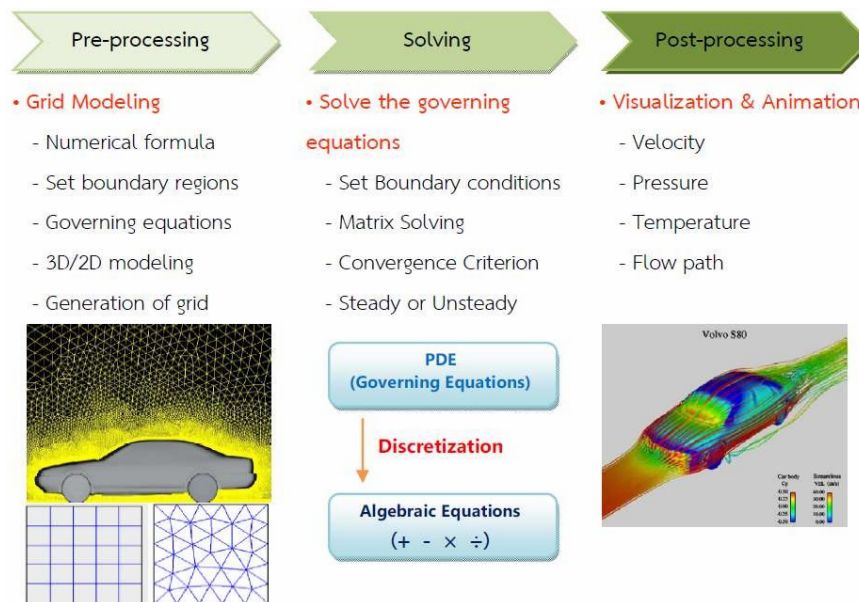


Figure 40: The CFD process [19]

Although CFD has become a remarkably useful tool in product development, it does not replace the need for experimentation. Table 3 shows the comparison developed by [19] between experiments and simulations.

Table 3: Comparison between experiments and simulations

Experiments	Simulations
Involves physical (quantitative) measurements of flow phenomena. One quantity is measured at a time.	Involves quantitative prediction of flow phenomena using a CFD software. All desired quantities can be measured simultaneously.
Measurements are taken at a limited number of points and time instants. Usually developed for a laboratory-scale model. Sources of error include: measurement errors, flow disturbances by probes, etc.	Analysis is carried out with high resolution in space and time. Can be designed for virtually any problem at realistic operating conditions. Sources of error include: modelling, discretization, iteration and implementation.
Experiments can be expensive and slow. Experiments are sequential and single-purpose.	Simulations are cheaper and faster. Simulations are parallel and multi-purpose.

[19]

Modern engineering has been greatly enhanced by developments in computer technology. At present, virtually all aspects of engineering design process have been computerized. FEA is based on the principle of simplifying a complicated object to make it easier to analyse. The idea of ‘simplifying’ an object implies discretization. FEA makes it possible to virtually test a product design by subjecting it to loading (mechanical, thermal or electromagnetic). The study can be applied in different fields of study including fluid flow, heat transfer, electrostatics or electromagnetics and structural or solid mechanics [20]. The procedure for carrying out FEA are as follows:

- i. Create the geometry.
- ii. Apply mesh to the geometry (a collection of elements and nodes).

- iii. Describe how physical quantities interact with each element.
- iv. Assemble the elements at the nodes to form an approximate set of equations for the entire model.
- v. Apply boundary conditions and loads.
- vi. Solve the system of equations
- vii. Calculate the required quantities and visualize (post-processing)

Table 4 presents parameters for PTC.

Table 4: Parameters for the PTC

Parameter	Symbol	Value
Collector width	W	5.0 m
Collector length	L	7.8 m
Collector focal distance	f	1.71 m
Collector aperture	Aa	39.0 m ²
Collector concentration ratio	C	22.74
Inner diameter of the receiver	Dri	66×10^{-3} m
Outer diameter of the receiver	Dro	70×10^{-3} m
Diameter of the inner cover	Dci	109×10^{-3} m
Diameter of the outer cover	Dco	115×10^{-3} m
Inner surface of the receiver	Ari	1.617 m ²
Outer surface of the receiver	Aro	1.715 m ²
Inner surface of the cover	Aci	2.671 m ²
Outer surface of the cover	Aco	2.818 m ²
Emittance of the receiver	ϵ_r	0.2
Emittance of the cover	ϵ_c	0.9
Absorbance of the absorber	α	0.96
Transmittance of the cover	τ	0.95
Reflectance of the concentrator	ρ_c	0.83
Intercept factor, IF	γ	0.99
Incident angle modifier (zero incident angle)	K ($\theta = 0^\circ$)	1
Incident angle	θ	0°
Maximum optical efficiency (zero incident angle)	$\zeta_{opt, max}$	75%

(15)

The working fluid used in the PTC is Syltherm 800. Data sheet for the working fluid was published [21].

Assumptions:

The following assumptions were made in modelling the collector:

- i. The collector surface is gray i.e. radiation properties are independent of wavelength.
- ii. The incident energy over the collector surface is uniform
- iii. The collector transmits thermal energy to the receiver and the ambient predominantly by radiation.
- iv. The thermal flux over the absorber is uniform.
- v. Contact thermal losses are negligible
- vi. The collector operates in steady-state conditions.
- vii. There is no variation in temperature along the receiver.

- viii. Due to the vacuum between the receiver and its glass cover, heat loss by convection in the receiver tube is negligible.
- ix. There is infinitesimal difference in temperature between the receiver and the fluid.
- x. Thermal losses at the contacts are negligible.

Considering the relative sizes of the receiver cover and the tube containing the working fluid, the glass cover is typically larger in surface area. Thus, we can consider the receiver tube as a small convex object surrounded by a large surface.

Computational Model of the Dehydrator

The development of computer technology has facilitated electronic development and analysis of computational models of complex geometries. Computers with high computing powers have been able to solve the three-dimensional Navier-Stokes equations. CFD is an emerging field in engineering, but has greatly reduced expenses incurred in product development. CFD was chosen over FEA for this study since FEA is not really designed to handle the strong convection typical in the analysis of fluid flow. This defect in FEA solution leads to convergence and stability problems in thermo-fluid simulation problems. FEA is more suited for structural analysis but can be used to solve some fluid problems. In contrast, CFD is stable and effectively handles the convection term found in the general Navier-Stokes [22].

Conclusion

Solar drying will continue to find applications, right from common traditional method of keeping items on the floor, mattress, tray or waterproof to dry. Of interest is how effective solar drying can be applied to obtain effective results, especially when large or commercial drying are to be used. The distributed -type active solar dehydrator- design that have supply of airflow across the trays horizontally provides the best performance in airflow and temperature distribution. By such applications optimum drying can be obtained.

REFERENCES

- [1]. Vanek, F and Albright, L. (2008). *Energy Systems Engineering: Evaluation and Implementation* McGraw Hill, New York, 168 – 295.
- [2]. Motahayyer, M., Arabhosseini, A. and Samimi-Akhijahani, H. (2019). Numerical Analysis of Thermal Performance of a Solar Dryer and Validated with Experimental and Thermo- graphical Data. *Elsevier*, 193: 692-705.
- [3]. Getahun, E, Delele, M., Gabbiye, N., Fanta, S., Demissie, P. and Vanierschot, M. (2021). Importance of Integrated CFD and Product Quality Modelling of Solar Dryers for Fruits and Vegetables: A Review, *Elsevier*, 220: 88-110
- [4]. Kalogirou, S. (2009). *Solar Energy Engineering: Processes and Systems*. 2nd Edition. Elsevier Inc., California, 140 – 250p.
- [5]. Mayur, P. and Patel, P. (2015). Experimental Investigation of Parabolic Trough Collector Solar Air Heater. *International Journal for Scientific Research and Development*, 3(9): 67-70.
- [6]. Gangloff, T., Steven, G. and Ferguson, S. (2014). *The Ultimate Dehydrator Cookbook*. Stackpole Books, Mechanicsburg, 17-120p.
- [7]. Isiaku, H. and Laah, E. (2021). An Experimental Study and Analysis on Solar Drying of Some Vegetables using Locally Fabricated Solar Food Dehydrator in Zuba, Abuja, Nigeria, *International Research Journal of Modernization in Engineering Technology and Science*, 3(10): 87 – 94.
- [8]. Chavhan, S., Balkar, S., Pawar, M., and Rathod, R. (2012). Experimental Analysis of Thermal Performance of Solar Food Dehydrator, *International Journal of Processing and Post- Harvest Technology*, 3(2): 203-205.
- [9]. Oyerinde, A. and Braimah, J. (2021). Design and Fabrication of Experimental Solar Food Dehydrator for Root Crops and Vegetables Drying, *African Journal of Sustainable Agricultural Development*, 2(2): 31-40.
- [10]. Mitchell, E. (2021). *Dehydrator Air Flow: Horizontal or Vertical?* dehydratorlab.com/vertical-air- flow-vs-horizontal-air-flow (Retrieved on 3rd August 2021).
- [11]. Stiling, J., Li, S., Stroeve, P., Thompson, J., Mjawa, B., Kornbluth, K., Barrett, D.M., (2012). Performance Evaluation of an Enhanced Fruit Solar Dryer using Concentrating Panels. *Energy Sustainable Development*, 16: 224–230.
- [12]. Banout, J. Ehl,P., Havlik, J., Lojka, B., Polesny, Z. and Verner, V. (2011). Design and Performance Evaluation of a Double-pass Solar Dryer for Drying of Red Chilli (*Capsicum annum* L.). *Solar Energy*, 85: 506 – 515
- [13]. Duffie, J. and Beckman, W. (2013). *Solar Engineering of Thermal Processes*. John Wileyand Sons, New Jersey, 168 – 170.
- [14]. Purusothaman, M. and Valarmathi, M (2018). Computational Fluid Analysis of Greenhouse Solar Dryer. *International Journal of Ambient Energy*, 1: 1-7.
- [15]. Bellos, E and Tzivanidis, C. (2018). Analytical Expression of Parabolic Trough Solar Collector Performance. *Designs*, 2(9): 1 – 17.
- [16]. Getahun, E, Gabbiye, N., Delele, M., Fanta, S. Gebreslasie, M., and Vanierschot, M. (2020). Effect of Maturity on the Moisture Sorption Isotherm of Chilli Pepper (Mareko Fana Variety). *Heliyon*
- [17]. Sileshi, S., Hassen, A., and Adem, K. (2022). Simulation of Mixed-Mode Solar Dryer with vertical Air Distribution Channel. *Elsevier*, 225: 1-11.
- [18]. Rakyat, M., Yeunyongkul, P., Wuttikid, K., Promdan, S., Nuntapap, Chaichana, C., Hokpunna, A., Chungcharoen, T., Ruttanadech, N., Srichai, P. and Munsin, R. (2021). Study of air Distribution in Tray Dryer using Computational Fluid Dynamics. *Engineering and Applied Science Research*. 48(6): 684 – 693.

- [19]. Sulaksana, K. and Thamkeng, P. (2014). *Heat Transfer and Fluid Flow Simulation with ANSYS*. [eng.sut.ac.th/me/2014/document/training/CAETraining\(Fluid\).pdf&ved=2ahUKEwib8Mmo8PL1AhWR3oUKHQdwDp0QFnoECDAQ&usg=AOvVaw2zWi-ilAAjWcNg7qNHpe8f](https://eng.sut.ac.th/me/2014/document/training/CAETraining(Fluid).pdf&ved=2ahUKEwib8Mmo8PL1AhWR3oUKHQdwDp0QFnoECDAQ&usg=AOvVaw2zWi-ilAAjWcNg7qNHpe8f) (Retrieved on 3rd August 2021).
- [20]. DOW (1997). Syltherm 800 Heat Transfer Fluid: Product Technical Data. DOW Chemical Company, Canada, 15.
- [21]. Chen X. and Liu, Y. (2015). *Finite Element Modelling and Simulation with ANSYS Workbench*. 2nd Edition. Taylor and Francis Group, New York, 1-50p.
- [22]. Cadence CFD (2023). *FEA vs. CFD: The Differences and Applications of Simulation Tools*. <https://resources.system-analysis.cadence.com/blog/msa2021-fea-vs-cfd-the-differences-and-applications-of-simulation-tools> (Retrieved on 20th February 2023).