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Optimizing Solar Drying Systems: A Comprehensive Study on an Innovative Design, Simulation, and Performance Assessment

Chibuzo V. Ikwuagwu[a,c*], Cajethan M. Nwosu[b,c], Boniface O. Anyaka[b,c], Godwin O. Unachukwu[a,c]

[a] Department of Mechanical Engineering, University of Nigeria, Nsukka, 410001, Nigeria
[b] Department of Electrical Engineering, University of Nigeria, Nsukka, 410001, Nigeria
[c] Africa Centre of Excellence for Sustainable Power and Energy Development (ACE-SPED), University of Nigeria, Nsukka, 410001, Nigeria

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ABSTRACT

Solar drying is a sustainable and environmentally friendly method for preserving food and agricultural products. This paper presents the design, development, and performance evaluation of an innovative solar dryer that incorporates three solar collectors spatially arranged at angles of 90^0 from each other on the horizontal plane for enhanced performance and phase change material (PCM). A passive solar dryer with three solar heat collectors has been designed and its performance simulated. It aims to improve the efficiency and reliability of solar drying processes, reducing post-harvest losses and energy consumption. Results from the system simulation using Ansys 2023 show a drying temperature range of 45-58ºC and air velocity flow of 10-15ms^{-1}, these distinct parameters necessary for effective drying are higher than the values reported in the literature. Also, the plots of the scaled residuals presented in this study suggests better convergence trends in the simulation and indicates how close the numerical solution is to a steady state and proves that this new design is a promising replacement for the old variants of solar dryers with one FPSC. In the final section, generalization of the study findings and possible design improvements have been pointed out.

1. Introduction

Solar drying is an environmentally sustainable and energy-efficient method of preserving agricultural products and commodities using solar energy [1]. It is a technology that harnesses the sun's energy to remove moisture from foods, crops, and other materials, reducing the risk of spoilage and extending their shelf life [2]. In some rural communities, many farmers use the open drying system to dry their harvested farm produce on the highways and streets. This drying method has its

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[*] Corresponding Author Email:chibuzor.ikwuagwu@unn.edu.ng

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attendant disadvantages, as rain, dew, and other weather conditions could disturb the drying process. Also, rodents and houseflies make the dried product unclean for human consumption [3].

An eco-friendly and cost-effective solar drying technique has gained prominence recently due to its potential to address food security, reduce post-harvest losses, and contribute to a greener future [4]. Solar drying involves harnessing incident solar thermal radiation on material surfaces to facilitate moisture evaporation within the drying chamber. As the sun's rays bearing heat energy strike a collector or absorber, the compartment between the collector and the glazing traps the heat energy, which is then transferred to the drying air. This heated air is circulated through the product being dried, causing moisture to evaporate and exit the system as water vapour. This results in dried products with acceptable moisture content, longer shelf life, improved quality, and preserved nutritional content [5]. Solar dryers come in various designs and sizes, ranging from simple, low-cost systems to more complex, high-efficiency models. A number of variables, including the kind of product being dried, the local climate, the resources that are available, and financial limitations, influence the choice of solar dryers [6]. Common types of solar dryers include direct, indirect, and mixed-mode designs, each with its own advantages and disadvantages. By harnessing the abundant and renewable energy provided by the sun, solar dryers offer a sustainable solution to the global challenges of food security, post-harvest losses, and environmental conservation [7].

Some advancements and modifications have been made by various researchers so as to improve or predict the performance of solar dryers. For instace, Salhi et al [8] conducted a reasearch on experimental and numerical investigation of the incorporation of an air temperature controller for indirect solar dryers and observed the importance and necessity of temperature control in solar drying systems, as well as the effectiveness of the CFD method in predicting system performance. Also, Mohammed et al. [9] optimized solar food dryer with varied air heater designs and found out that their optimised solar dryer was very suitable for successfully drying fruits and vegetables in Iraq's atmosphere through practical experiments. Furthermore, Yematawu et al. [10] conducted a study on experimental testing on the performance of solar dryer equipped with evacuated tube collector, rock bed heat storage and reflectors. They observed that In comparison to the situation of utilizing evacuated tube collector (ETC) alone and 30 % of the drying period in relation to the open sun, the introduction of a reflector on the collector increased the average net heat obtained from the collector by 5.1 %. In another instance they noticed that the slice's moisture content was lowered to 12.37 % in under eight hours using ETC alone, while the dryer's efficiency was 29.82 %.

However, the use of flat plate solar colloectors (FPSC) makes solar dyers most efficient in drying as they don’t use conventional enrgy from fossil fuel power plants [11]. FPSC are the most basic, low-cost, and widely used solar energy collecting devices [12]. Modifications in design, insulating material, process optimization, and enhanced working fluids (nano-fluids) of various types have all contributed to the progressive enhancement of FPSC [13]. Simo-Tagne et al. observed that any modification in one of the parameters involved in designing FPSC may cause compatible changes in other parameters [14]. Observations based on various researchers' contributions reveal that design elements, processes, and working fluids have functional linkages that usually result in its improved system working efficiency [15].

Krabch et al in their study noted that technological advancements and technical adjustments constantly present a chance to improve the existing solar dryer system's efficiency by lowering energy losses, material and maintenance costs [16]. The best thermal efficiency will result from optimizing these values and other necessary parameters for solar dryers’ enhanced performance.

To improve the performance of solar dryers, Tesfaye et al. conducted a series of tests to investigate the performance of a solar tunnel dryer for drying ginger. The team utilized two axial flow fans to supply hot air to the dryer with a power rating of 28 W, a supply voltage of 220 V, and a 50W photovoltaic (PV) module [17].

Gunawan et al., on the other hand, developed an efficient, affordable, and self-sufficient intelligent energy system that will be used in agriculture for storage or drying purposes by measuring the energy needs for the optimal drying system. They estimated and assessed the critical energy needs for such new systems in order to optimize and design such smart solar dryer (SSD) system, primarily for Indonesia's agricultural needs [18]. Predolin et al developed, built, and tested an indirect solar dryer with natural convection for use in remote areas [19], it consisted of three main components: an absorber plate, a dryer chamber, and an exhaust duct. The position of the absorber plate in their device can be changed to shift airflow from the upper face to both the upper and lower faces (double passage). Temperature, humidity, and atmospheric pressure sensors were installed at the air inlet and outlet, allowing for the evaluation of equipment performance. Hashemian and Noorpoor [20] conducted a study where they introduced a ground-breaking multi-generation plant utilizing solar and wind energy. They reported that parabolic trough solar collector optimization is crucial as it contributes up to 57% of exergy destruction. They also, in another study, employed a Multi-criteria optimization approach based on a genetic algorithm to specify the optimum design of solar and biomass-based multi-generation system considering the improvement of thermodynamic and thermoeconomic performance [21], their works, however, butress the fact that existing solar dryers still has various rooms for improvements.

Ashmore et al. [22] con ducted a research on a novel thermal characteristics of drying banana slices in an indirect dryer are presented for four different experimental drying conditions in the forced convection mode, their observations was that increasing the drying chamber airflow velocity results in faster moisture removal during sunshine hours for the 24 h tests. Furthermore, Aacharya et al. [23] developed a solar dryer with an incorporated heat exchanger and concluded that the highest tested airflows provide higher air circulation for effective heat and mass transfer from the product to the surrounding air for drying. On the other hand, Nguyen et al. [24] developed an advanced machine learning for prognostic analysis of drying parameters of banana slices in an indirect solar dryer. There findings illustrate the practical applicability of the XGBoost and LightGBM models in food drying operations towards optimizing drying conditions, improving product quality, and reducing energy consumption.

In line with the aforementioned advances in solar dryers, Kumar et al created a box-type natural convective solar dryer to test the drying performance of wood chips. Their research and tests yielded promising drying results with high efficiency. However, they proposed that the dryer's design could be further improved by hybridization with an external heat source [25].

However, the efficiency of conventional solar dryers can be limited due to variations in solar radiation and environmental conditions [26]. To address these challenges, this paper introduces an innovative solar dryer design that combines the benefits of three FPSCs and phase change material (PCM) to enhance the drying process while maintaining the organoleptic properties of the dried products. The integration of these components aims to enhance the system's performance and improve the overall drying process.

Various classifications of solar dryer exist in practice. Solar dryers can be classified based on various factors such as design, operating principle, and purpose [27]. These classifications provide an overview of the different types of solar dryers available. The selection of a specific dryer depends on factors such as the type and quantity of the product to be dried, available resources, climate conditions, and desired drying output [28]. Presented here are the basic classifications of solar dryers.

1.1 Passive and Active Solar Dryers

1.1.1 Passive solar dryers rely solely on natural convection and heat transfer to dry the product. They do not require any mechanical or electrical components and are more suitable for small-scale and low-cost applications.

1.1.2 Active solar dryers use mechanical components like fans or blowers to enhance air circulation. They have a higher drying rate and are generally used for larger-scale drying operations.

1.2 Direct and Indirect Solar Dryers

1.2.1 Direct solar dryers expose the product directly to solar radiation for drying. They are simple and have lower construction costs. However, there is a risk of contamination and excessive temperature rise, which may have adverse effect on the quality of the product.

1.2.2 Indirect solar dryers separate the product from solar radiation using a separate solar collector. The collected heat is then transferred to the drying chamber using a heat exchanger. Indirect dryers help maintain better control over temperature and humidity, reducing the risk of product damage or degradation.

1.3 Batch and Continuous Solar Dryers

1.3.1 Batch solar dryers are designed to dry a fixed quantity of product at a time. The product is loaded into the drying chamber, and the drying process is carried out until the desired moisture content is achieved. These dryers are suitable for smaller-scale operations and can be easily constructed and maintained.

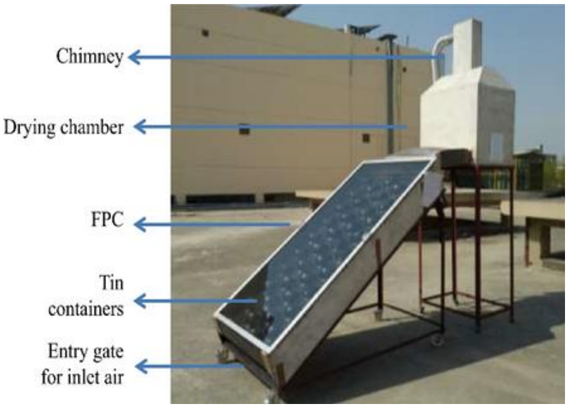

Figure 1. Passive solar dryer with PCM containers [29]. (This is an example of a passive solar dyer with sensible heat storage)

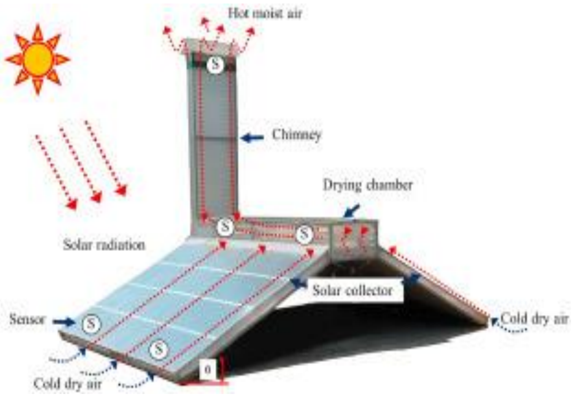

Figure 2. Completed double-sided solar collector dryer [30]. (This is an example of a passive solar dyer)

Figure 3: Pictorial view of the desiccant integrated solar dryer with reflected mirror [31]. (This is an example of an active solar dyer)

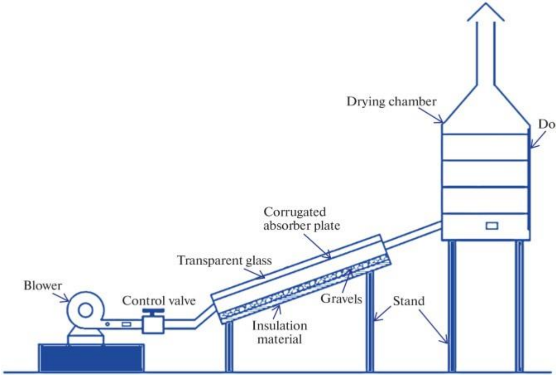

Figure 4: Schematic view of a forced convective solar dryer [31]. (This is an example of an active solar dyer)

Figure 5: Pictorial view of greenhouse solar dryer used for chilli drying in Thailand [32]

1.3.2 Continuous solar dryers allow continuous product flow through the drying chamber. The product is loaded at one end and continuously moved through the dryer, while the fresh product is loaded at the other. These dryers are typically used for larger-scale industrial drying and is more energy intensive.

1.4 Mixed-Mode Solar Dryers

Mixed-mode solar dryers combine solar energy with other heat sources, such as biomass, electricity, or fossil fuels. This allows for greater control over drying parameters and can overcome the limitations of relying solely on solar energy. Mixed-mode dryers are commonly used in areas with limited sunlight or during periods of low solar radiation.

Various indirect-passive solar dryers that use FPSC as their source of thermal energy make use of only one or two FPSCs as shown in Figures 1 and 2. However, the efficiency of conventional solar dryers can be limited due to variations in solar radiation, design and environmental conditions as rightly observed by [33].

To address these challenges, this paper introduces an innovative solar dryer, by way of design and simulation concept that combine the benefits of three FPSCs and phase change material (PCM) to enhance the drying process while maintaining the organoleptic properties of the dried products. The integration of these components aims to enhance the system's performance and improve the overall drying process. Figures 1 through 5 show various designs of solar dryer that have been in use for some time now. On the other hand, researchers have tried to modify basic solar dryer design with the sole aim of improving their performances and drying efficiencies.

In view of the forgoing, taking into cognizance various designs and operations of solar dryers and aligning critically to the fundamental phenomenon that underscores the art of solar drying, this research presents a novel design and performance simulation of a solar dryer. It shows that it shows a more energy intensive system by incorporating three flat plate collectors as a sensible heat source in a solar dryer so as to boost the system's performance and efficiency. The significance of this study is that it shows the possibility of making use of three FPSCs other than using only one FPSC or double sided FPSC as used by Pruengam et al [30] (shown in figure 2). This research also shows that the performance of a solar dryer is improved by making use of three FPSCs. The feasibility of this design is basically shown by way of simulation using Ansys Software in this study.

2. Materials and Methods

Materials with good thermal conductivity and resistance to weathering were selected. Plywood cladded with aluminium foil was used in the simulation. Low-emissivity coatings on the collector surfaces were used to help improve its efficiency. The drying chamber was designed to accommodate the type and quantity of products to be dried. Good insulation was also ensured in the design to minimize heat loss. Due to the necessity for air mass flow from the drying chamber to the surroundings, an efficient airflow system was developed that evenly distributes heated air over the drying trays.

Solar fans were used to create forced convection necessary for sucking away moist air to ensure uniform drying. An efficient chimney was incorporated into the dryer design to take away the saturated air from the dryer. As a sensible heat energy storage, a phase change material was incorporated into the bed of the solar collectors to store heat during the day and release it at night to maintain consistent drying conditions. General safety features were incorporated in an Arduino circuit to protect against overheating, over-drying, and fire hazards. Temperature and humidity sensors with automatic shut-off mechanisms were implemented.

Basically, material selection tends to be an issue in every design. The materials used in the dryer are food-safe and suitable for the specific products being dried. Also, innovation with affordability was well balanced in this study as the cost of materials and technology can impact the feasibility of the solar dryer [19]. The environmental footprint of the solar dryer was considered, including its manufacturing process and end-of-life disposal. The solar dryer designed in this project has an easy-to-use interface for operators to set drying parameters and monitor progress. Designing an innovative solar dryer such as this requires careful consideration of various factors to ensure its efficiency, effectiveness, and sustainability. Conventionally FPSC are usually deployed in solar dryer designs due to simplicity, ease of arrangement and availability of materials required for construction. Since drying is the primary use of the system conceived in this work, FPSCs are adopted to generate the heat energy needed. Also, the tilt angle that defines the orientation of the solar collector in relation to Hemisphere-facing is a very important parameter. Researchers have often chosen tilt angles ranging from 0^0 to 60^0.

Nevertheless, in this work, the tilt angle is determined and optimized using Ansys modelling software to enhance exposure and maximize the rate of solar energy collection. This resulted in using a tilt angle of 17^0 for this work. This tilt angle corresponds to the tilt angle for the Nsukka region of Enugu State, Nigeria, as supported by [34]. By using the formula:

Generally,

$$\beta = 10° + \text{lat}\varphi \qquad (1)$$

We obtain that $\beta = 10° + 7° = 17°$ (according to [34], latφ for Nsukka is approximately 7^0).

The tilt angle of Flat Plate Solar Collector (FPSC) typically depends on the geographical location to maximize solar energy absorption. Here are the approximate recommended tilt angles for flat plate solar collectors based on the latitude:

- Equator (0° latitude): The recommended tilt angle is usually between 0° to 5°.
- Higher latitudes (above 60° latitude): The tilt angle can be as high as 60° or more. This ensures adequate sunlight absorption during the lower sun angle in these regions.

It is important to note that these are general recommendations, and actual tilt angles may vary based on various factors such as seasonal variations, specific climate conditions, and the application of the solar collector [35]. Other factors like aesthetic considerations or installation practicalities may also influence the chosen tilt angle.

2.1 FPSC Arrangement

FPSCs are the most basic, low-cost, and widely used solar energy collecting devices. Modifications in design, insulating material, process optimization, and enhanced working fluids (nano-fluids) of various types have all contributed to the progressive enhancement of flat plate solar collectors. Any modification in one of the parameters may cause compatible changes in the others. Observations based on various researchers' contributions reveal that design elements, processes, and working fluids have functional linkages that usually result in increased system working efficiency [36]. Technological advancements and technical adjustments constantly present a chance to improve the existing system's efficiency by lowering energy losses and material and maintenance costs. The best thermal efficiency will result from optimizing these values [37].

In the present work, the conceptual solar dryer incorporates three flat-plate collectors, two located sideways opposite each other and the third one at an angle 90^0 with the other collectors on the horizontal plane (Figure. 3). The arrangement of the dryers is such that they are synchronized to capture both diffused and direct solar radiation and transfers captured thermal energy from the sun to the core of the drying chamber. In this way, not only is the quantity of heat energy delivered enhanced, but it becomes usefully available for the task of drying.

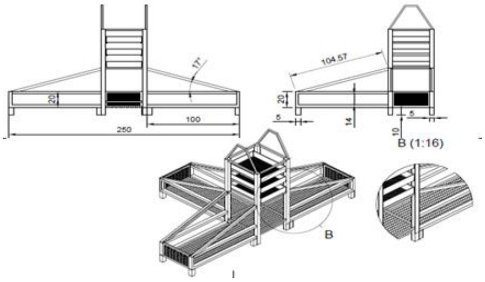

Figure 6. Isometric view of the solar dryer

Figure 7. Designed Flat Plate Solar Collector

Working Principle:

The working principle of the solar dryer is outlined as follows:

- The solar collectors capture and enhance the thermal capacity of the solar radiation in the drying chamber.
- The thermal energy is transferred to the drying chamber, where the PCM absorbs and stores excess heat unavailable for drying to be released at night. However, this mechanism is greatly influenced by the degree of radiation during the day, the space between the PCM holder facing the drying plate, the humidity at night, the air-velocity and some other weather conditions.
- During the nighttime or periods of low solar radiation, PCM releases stored heat to maintain a consistent drying chamber temperature.
- Air circulation and ventilation systems ensure efficient moisture removal from the drying chamber

Mathematical Formulation of the FPSC Parameters

From [16],

$$IA_c = Q_u + Q_{cd} + Q_{cv} + Q_R + Q_\rho \quad (2)$$

Also,

$$Q_{cd} + Q_{cv} + Q_R = Q_L \text{ [38]} \quad (3)$$

Hence combining (2) and (3) yields:

$$I = \frac{Q_u + Q_L + Q_\rho}{Ac} \quad (4)$$

If τ is the transmittance of the top glazing and I_T is the total solar radiation incident on the top surface, then

$$IA_c = \tau I_T A_c \text{ [39]} \quad (5)$$

Hence,

$$I = \tau I_T \quad (6)$$

According to Rahman et al [40], the reflected energy from the absorber is given by the expression:

$$Q_\rho = \rho\tau I_T A_c \quad (7)$$

Where ρ = the reflection coefficient of the absorber. Substitution of equations. (5), (6) and (7) in equation (4) presents:

$$\tau I_T A_c = Q_u + Q_L + \rho\tau I_T A_c \quad (8)$$

Also,

$$Q_u = \tau I_T A_c(1-\rho) - Q_L \quad (9)$$

Since for an absorber:

$$\alpha = (1 - \rho) \text{ [41]} \quad (10)$$

Substituting equation (10) into (9) yields:

$$Q_u = (\alpha\tau)I_T A_c - Q_L \quad (11)$$

Q_L is composed of different convection and radiation parts. Joshua et al [29] presented Q_L in the following form:

$$Q_L = U_L A_c(T_c - T_a) \quad (12)$$

2.2 Mathematical Formulation of the Dryer

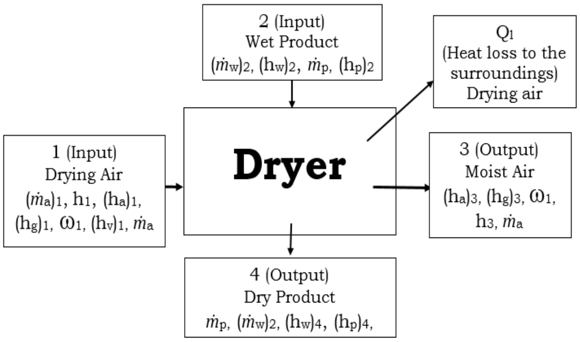

Figure 8: Schematic diagram of the drying process inside the drying chamber

2.2.1 Mass Balance Equations

Writing a mass and energy balance equation for the dryer shown in Figure 6. we consider three elements: air, water and the product. This approach was adopted by [42] and [43]. Hence we can write the mass balance of these three components as follows:

Air: $(\dot{m}_a)_1 = (\dot{m}_a)_3 = \dot{m}_a$ (13)

Water: $\omega_1 \dot{m}_2 + (\dot{m}_w)_2 = \omega_3 \dot{m}_a + (\dot{m}_w)_4$ (14)

Product: $(\dot{m}_p)_2 = (\dot{m}_p)_4 = \dot{m}_p$ (15)

2.2.2 Energy Balance Equations

Recall from the law of conservation of energy (First Law of Thermodynamics) that the sum of energy input into a system is equal to the sum of energy output from the system. Hence, the energy balance of the drying system can be written thus:

$$\dot{m}_g h_1 + \dot{m}_p (h_p)_2 + (\dot{m}_w)_2 (h_w)_2 = \dot{m}_a h_3 + \dot{m}_p (h_p)_4 + (\dot{m}_w)_4 (h_w)_4 + Q_1 \quad (16)$$

where,

$h_1 = (h_a)_1 + \omega_1 (h_g)_1$ [43] (17)

$h_3 = (h_a)_3 + \omega_1 (h_g)_1$ [43] (18)

The heat loss from the drying chamber is given by:

$Q_1 = \dot{m}_a q_1$ (19)

2.2.3 Exergy Balance Equations

Similarly, the exergy balance equations can be derived the same way we did for the energy balance of the entire drying system as follows:

$$\dot{m}_a e_1 + \dot{m}_p (e_p)_2 + (\dot{m}_w)_2 (e_w)_2 = \dot{m}_a e_3 + \dot{m}_p (e_p)_4 + (\dot{m}_w)_4 (e_w)_4 + \dot{E}_q + \dot{E}_d \quad (20)$$

The values of $e_{1,} e_3, e_p, E_q$ *and* E_q is calculated using thermodynamic relations in Ansys software

2.3 Mathematical Modeling and Simulation Approaches

Simulation approaches can be valuable tools for predicting solar dryer performance. They allow for evaluating different design parameters and operating conditions without costly and time-consuming experimental trials. There are three common simulation approaches used to predict solar dryer performance, namely Computational Fluid Dynamics (CFD), Finite Element Method (FEM) and System-level Modelling [44].

For clarity and more accurate results, the CFD simulation approach was employed in this research using Ansys 2023 R2 software. This approach is supported by [45]. Equations 1, 4, 12 and 16 are basically the input data used for the dryer simulation.

2.4 Computational Fluid Dynamics (CFD)

CFD simulations involve solving the governing equations of fluid flow, heat transfer, and radiation in a solar dryer. This approach provides detailed insights into the dryer's flow patterns, temperature distributions, and drying rates within the dryer. CFD simulations can account for geometry, materials, airflow rates, and solar radiation conditions. By analyzing the simulation results, the design and operation of solar dryers can be optimized to improve their performances.

The system was simulated in Ansys 2023 R2 software to evaluate its performance. Key performance parameters include: plot of scaled residuals, plot of enthalpy changes, temperature distribution in the solar collectors and the drying chamber and the velocity streamline of the drying air.

2.5 Basic Simulation Assumptions

These 8 basic assumptions were made when carrying out simulation study on optimizing solar drying systems:

- *Constant solar radiation*: Assuming a constant solar radiation intensity throughout the day and year, which may not be the case due to seasonal and weather variations.
- *Uniform temperature distribution*: Assuming a uniform temperature distribution within the drying chamber, which may not be the case due to heat transfer variations.
- *Constant air flow rate*: Assuming a constant air flow rate throughout the drying process, which may not be the case due to changes in temperature and humidity.
- *No heat loss*: Assuming no heat loss through the system's insulation and boundaries, which may not be the case due to thermal conductivity and radiation.
- *No shading or obstruction*: Assuming no shading or obstruction of the solar collector or drying chamber, which may not be the case due to surrounding objects or weather conditions.
- *Constant material properties*: Assuming constant material properties (e.g., thermal conductivity, specific heat capacity) throughout the drying process, which may not be the case due to changes in temperature and moisture content.

- *No air leakage*: Assuming no air leakage into or out of the drying chamber, which may not be the case due to imperfect sealing or cracks.
- *No condensation*: Assuming no condensation occurs within the system, which may not be the case due to changes in temperature and humidity.

3. Results and Discussion

The temperature within the system shows that the air around the solar heat absorber which in this design is corrugated aluminum sheet, experiences the highest temperature compared to other regions. It can be seen in figures 9 and 10 that the temperature reduces as it moves up to the drying chamber for drying of food materials with a maximum drying temperature in the range of 45 to 58^0C. This is due to the ambient temperature being set to 27^0C. During sunshine hours when the ambient temperature gets up to 35^0C the temperature in the drying chamber was observed to go up to 58^0C, which is efficient for drying. The simulated maximum drying temperature of this solar dryer design is higher than 54.1^0C [46] and 55^0C [47] as recorded by some researchers.

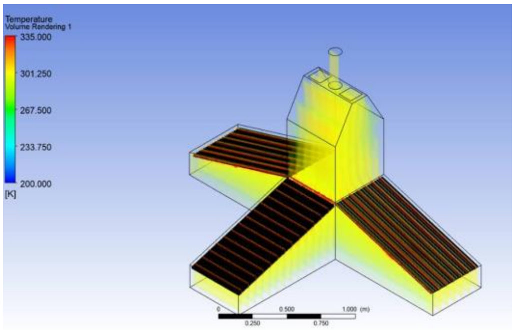

Figure 9: Pictorial view of the temperature volume rendering in the solar dryer

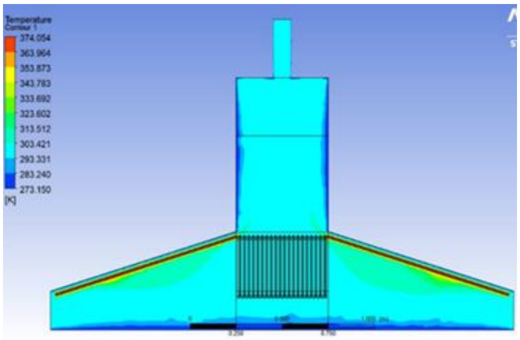

Figure 10: 2-D view of the temperature distribution in the solar dryer

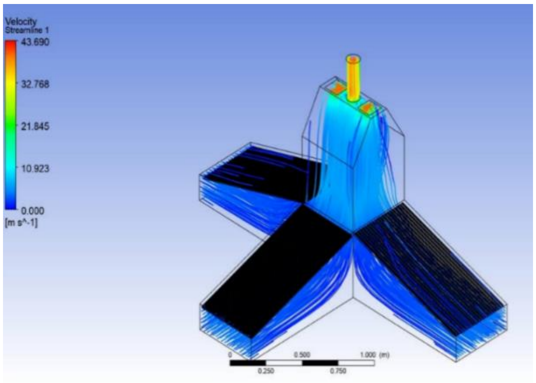

Figure 11: Pictorial view of the velocity streamline in the solar dryer

Figure 11 shows the velocity of the air at the range of 10 to 15 m/s throughout the system as it sucks the air from the inlet and moves it throughout the medium, and is expelled to the atmosphere. The airflow velocity of the proposed system greatly surpasses the value of 2 m/s reported by [48]. The air velocities at various points are depicted with a colour contour, showing that the airflow at the fan outlet has the highest velocity. The reason is that moist air is expected to be taken off the drying chamber faster to engender faster drying of foodstuffs.

Figure 12 shows the plot of scaled residuals, which measure the solution's convergence in a CFD lower- are noticed. It suggests better convergence trends in the simulation and indicates how close the numerical solution is to a steady state. The plot of the scaled residuals show that the residuals decrease and stabilize at acceptable levels over time.

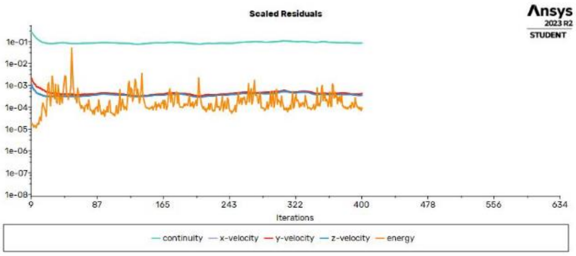

Figure 12. Plot of Scaled Residuals in the solar dryer

Enthalpy and volume are crucial parameters for analyzing heat transfer and energy exchange during drying. The plot shows how the enthalpy of the material changes as its volume decreases due to moisture removal during drying. Figures 13 to 15 show the volume-enthalpy, average-enthalpy and enthalpy-min in the solar dryer, respectively.

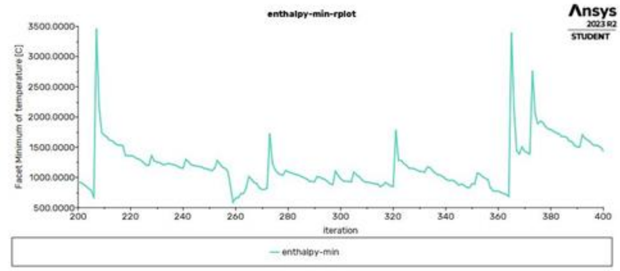

Figure 13: Plot of volume-enthalpy in the solar dryer

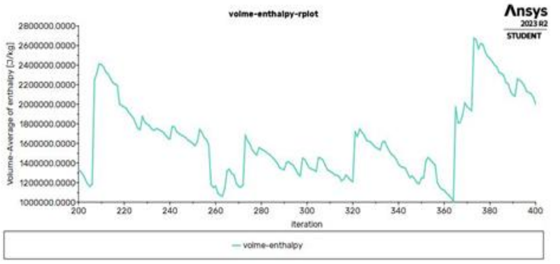

Figure 14: Plot of average enthalpy in the solar dryer

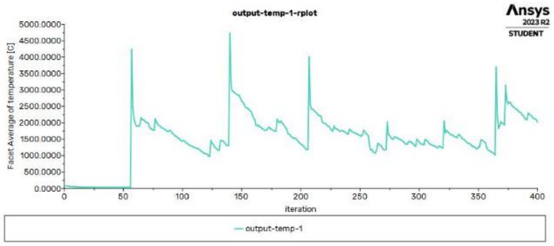

Figure 15: Plot of enthalpy-min in the solar dryer

The average enthalpy plot represents the variation of enthalpy with respect to time during the drying process. It shows how the system's enthalpy changes as the material inside the solar dryer undergoes drying. The system's enthalpy typically starts at an initial value and decreases gradually as drying progresses. This decreasing trend indicates the removal of moisture and reduction in enthalpy. Some points of inflexion are noticed. These indicate transitional phases or variations in the drying process, such as initial heating, constant drying rate, falling drying rate, or equilibrium moisture content. By analyzing the trends and characteristics of these plots, engineers and researchers can assess the efficiency and effectiveness of the drying system, optimize its design, and make necessary adjustments to improve its performance.

4. Conclusions

A passive solar dryer with three solar heat collectors has been designed, and its performance has been simulated and optimized. The simulated results demonstrate that the innovative solar dryer presented in this work is a viable project with the proclivity to replace the conventional passive solar dryers that utilize only one FPSC for its drying operation. Results from the system simulation using Ansys 2023 show a maximum drying temperature of 58^0C and air velocity flow range of 10 – 20 ms^{-1}.

Further research is warranted to optimize system design and scale its implementation for broader agricultural applications. Also, future research should focus on optimising collector integration and control strategies, long-term field testing and monitoring, economic feasibility and scalability for commercial use, integration with smart control systems and remote monitoring should be investigated by using data mining for a simulated case study. Practically generated energy, power conversion efficiency, energy efficiency and exergy efficiency have been analyzed as key performance indicators for evaluation of the solar dryer system dynamics.

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Nomenclature

I	Total radiation incident on the absorber's surface (Wm^{-2})
I_T	Total solar radiation incident on the top surface (Wm^{-2})
A_c	Collector area (m^2)
Q_u	Rate of useful energy collected by the air (kJ/s)
Q_{cd}	Rate of heat loss by conduction (kJ/s)
Q_{cv}	Rate of convective losses from the absorber (kJ/s)
Q_R	Rate of re-radiation of long wave from the absorber (kJ/s)
Q_ρ	Rate of heat loss from the absorber through reflection (kJ/s)
τ	Transmittance of the top glazing
α	Plate absorptance

β	Collector tilt angle (degrees)
φ	Latitude (degrees)
U_L	Overall heat transfer coefficient of the absorber (Wm–2K–1)
Tc	temperature of the collector’s absorber (K)
$\dot{m}_a$	Mass flow rate of air (kg/s)
$\dot{m}_p$	Mass flow rate of moist products (kg/s)
$\dot{m}_w$	Mass flow rate of water content (kg/s)
□	Humidity ratio of air
h	Specific enthalpy (kJ/kg)
h_a	Specific enthalpy of air (kJ/kg)
h_p	Specific enthalpy of moist products (kJ/kg)
h_w	Specific enthalpy of water content (kJ/kg)
h_g	Specific enthalpy of at saturated vapour state (kJ/kg)
h_v	Specific enthalpy of vapour (kJ/kg)
e	Specific exergy (kJ/kg)
e_w	Specific exergy of water content (kJ/kg)
e_p	Specific exergy of moist product (kJ/kg)
$\dot{E}_q$	Rate of exergy flow for heat loss (kJ/s)
$\dot{E}_d$	Rate of exergy flow for destruction (kJ/s)
Q_l	Heat loss (kJ/s)

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