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Heat Transfer Analysis of a Concentrated-Type Solar Dryer for Ginger

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Keywords

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Heat Transfer
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Abstract

In recent years, global concern about the preservation of agricultural products for usage and exports through drying has been outstanding. Solar Parabolic Trough Collectors (SPTC) are used to dry various agricultural products for effective moisture removal. A heat transfer fluid (HTF) flows through a receiver tube pipe that absorbs solar radiation reflected from the stainless-steel sheet surfaces of the SPTC. In order to reduce the heat losses, the pipe was linked through a flexible, thermally insulated cross-linked polyethene pipe to the copper tubes inside the drying chamber. The heat transfer analysis of the SPTC is essential to understand the thermal behavior and its performance during the drying process. This paper examined the heat exchanges developed in the designed concentrated-type solar dryer, and the heat transfer rates in the receiver tube and the drying chamber, as well as the heat transfer coefficients for the solar drying of ginger, were determined. The thermal analysis of the convective heat exchanges within the receiver tube and the drying chamber is presented. The heat transfer coefficients hRec and hDC for the convective heat transfer process in the receiver tube and the drying chamber were 1372.48W/m.K and 17.60W/m.K, respectively. The dryer's thermal efficiency was 30%, showing considerable moisture removal from the ginger samples. The mean temperature difference between the drying chamber and the ambient showed a considerable increase of about +11oC. This resulted in considerable moisture removal, and the final moisture content achieved by the concentrated solar dryer for the ginger samples was 11.1%, compared to the 23.74% achieved by the open-air solar (OAS) drying method.

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1. INTRODUCTION

In order to minimise post-harvest losses and ensure crop availability for future use, crops are typically preserved through drying. In order to keep crops from spoiling, moisture must be removed. Inadequate techniques for preserving agricultural products, which are generated in greater numbers during harvest, are a common issue faced by Nigerian farmers. Ekechukwu (2010), related that the standard open-air solar drying method is minimal, causing crop spoilage due to inadequate drying, rodent, bird and insect encroachment, and mildews attack. Ebewele and Jimoh (1981) also asserted that crop exposure to harsh weather conditions like rain, dust, and wind is one of the drawbacks of insufficient drying techniques. Fumen et al. (2003) related that crop spoilage occurs annually and is valued at millions of dollars. However, these restrictions made it necessary to use dependable solar technologies for drying procedures. The majority of agricultural fields now use solar technology. Because solar thermal technology is abundant, renewable, and non-polluting, it is quickly gaining attraction in the energy-saving market. Various sun dryer types have been developed in various parts of the world.

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The two categories of solar dryers are forced-convection and naturally convection. Airflow generated by a fan or blower powered by fossil fuel, electricity, or solar panels powers the former, whilst buoyancy-induced airflow powers the latter. Because of its high rate of ginger production, Okafor (2002) claimed that Nigeria continues to be the country's top exporter of ginger. Significant ginger production occurs in Nigeria's Benue, Niger, Gombe, Nasarawa, and Kaduna states. Still, Kaduna state provides roughly 95% of Nigeria's total ginger production. Nigerian ginger production, estimated at 110,000 metric tonnes in 2005, climbed to roughly 60% after five years, with 90% of the crop being exported in dried form and 10% being consumed fresh locally (Gucheman, 2010). Njoku et al. (1995), declared that Nigerian ginger is known for its strong scent, pungency, and oil and oleoresin content. For worldwide, ginger is one of the main ingredients for the production of wine, meat, soft beverages, bakery goods, perfumes, and toiletries. It is possible to use dried ginger both medicinally and as a solitary spice. In certain nations, ginger is also used to treat particular illnesses like cholera, dyspepsia, rheumatism, cancer, nausea, growths in the throat, cataracts, pulmonary and neuralgia, and fabric disease.

Processing ginger involves first selecting the best pieces, then giving them a thorough washing and soak. Next, it is split and peeled, and dried until the moisture level reaches 7–12% (Ebewele & Jimoh, 1981). Because of insufficient and subpar drying procedures, the majority of ginger produced in Nigeria and beyond is of low quality and falls short of the requirements and expectations of most importers.Traditionally, ginger is sun-dried in an open yard in only one layer to produce a brown, unevenly wrinkled surface that reveals a dark brown colour when cracked. There are various kinds of dried ginger available, including slices, splits, and entire dried ginger. Direct solar drying and indirect solar drying are the two primary forms of solar drying. Compared to the open-air drying method, the solar dryer has five major advantages: it is more economical, hygienic, faster, more efficient, and healthier (Tiris et al., 1995). Augustus Leon et al. (2002) categorised the drying system based on the type and layout of solar energy use, as seen in Figure 1.

According to Njoku et al. (1995), the ginger produced in Nigeria has high oil and oleoresin content, pungency and aroma. Ginger processing after harvest entails first sorting out the good ones, after which they are thoroughly washed and soaked. It is then split and peeled before drying to a moisture content of 7-12% as stated by Ebewele and Jimoh (1981). Most ginger processed in Nigeria is of low quality and falls below most importers' expectations and specifications due to inadequate and sub-standard drying processes. There are two main types of solar drying namely: (i) Direct solar drying and (ii) Indirect solar drying.

The natural convection drier, sometimes referred to as an active sun dryer, works by moving hot air across the surfaces of the crop that has to be dried. When solar radiation strikes the dryer's glass cover, some of it is absorbed by the cabin dryer and some is reflected back into space. The temperature of the crop rises significantly as a result of the absorbed solar energy being reflected back from the crop surface and the remaining portion being absorbed into the crop. In contrast to an open sun drying system, a glass cover prevented the long wavelength radiation from escaping to the atmosphere, which decreased convective losses within the dryer and raised the drying chamber and crop temperatures considerably (Tiris et al., 1995). Despite being less portable than direct dryers, indirect solar dryers frequently show higher efficiency and may dry more agricultural products, according to Sharma et al. (2009). The main drawback of utilizing a direct solar dryer is eliminated with this type of dryer since the agricultural product is not exposed to sunlight directly. To get the most solar energy, the solar collectors need to be positioned correctly. When the solar collector surface was orientated perpendicular to the sun, more solar energy was typically captured. The natural convection concept also aids in air movement when the solar collector is tilted at an appropriate inclination. The solar dryer is made out of a drying chamber that holds the trays or shelves that hold the farm produce and a collector that heats the air (Sharma et al., 2009). A thorough analysis of different solar energy drying system designs, construction specifics, and operating principles was carried out by Ekechukwu and Norton (1999). According to their research, well-designed forced convection (active) solar dryers operate more efficiently and are easier to regulate than natural-circulation (passive) models. In this study, the ginger was dried using the indirect (active) solar dryer concept.

Augustus Leon et al. (2002) classified the drying system according to the mode and design of solar energy utilization, as seen in Figure 1. Drying, an intricate procedure of concurrent heat and mass transfer, is of significant importance in various industries. Initial and final moisture content, drying air temperature, relative humidity, and velocity are some of the variables that affect how much energy is needed to dry a particular product (Shukla & Sahu, 2019). Several investigations have been carried out regarding the heat transfer analysis of solar dryers to ascertain the heat transfer coefficient and augment efficiency (Alimohammadi et al., 2020). Sansaniwal and Kumar (2015) reported that in open-air drying settings with natural convection, ginger's convective heat transfer coefficient was 26.25 W/m^2, and the hybrid drier has a higher drying rate than open sun drying, with an overall drying efficiency of 13% and 18% in the summer and winter, respectively.

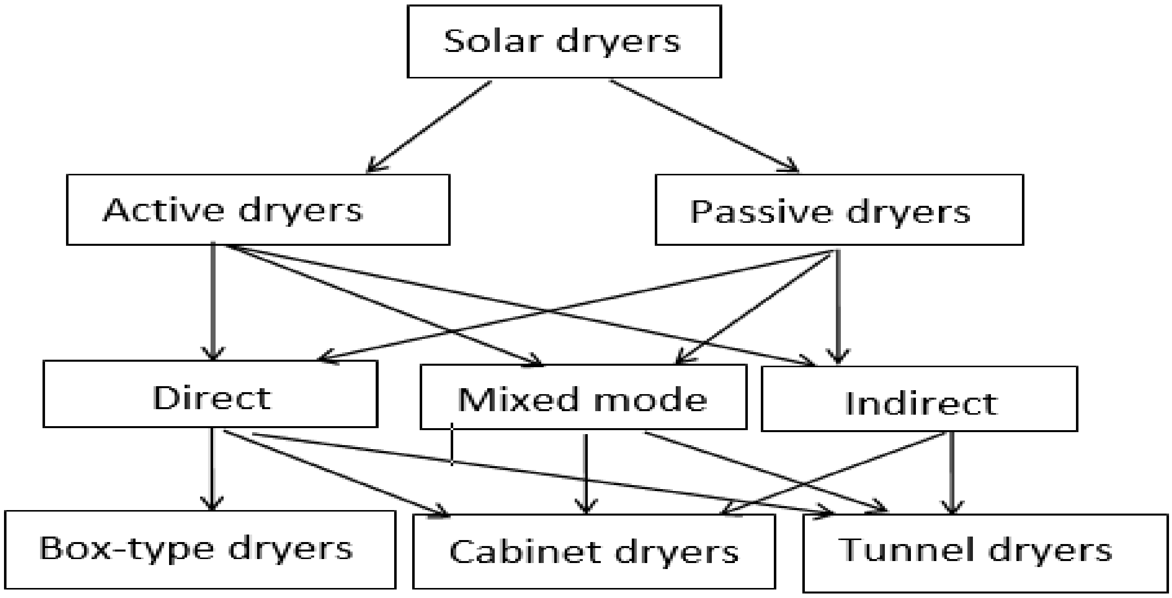

Figure 1. *Classification of solar heating modes and dryers (Augustus Leon et al., 2002)*

A straightforward and useful program that allowed the concentrator's parameters to be changed for assessing the thermal performance was created by de Oliveira Siqueira et al. (2014) after they developed and implemented a mathematical model to compute heat transfer and flow parameters harnessed to parabolic trough solar collectors. The software proved effective as a design tool since it is possible to determine the thermal efficiency and optical and thermal losses, among other things. The mathematical model that was constructed was logical. Padilla et al. (2011) created a thorough heat transfer model for the thermal analysis of solar receivers with parabolic troughs. More precise correlations and a thorough investigation of radiative heat transfer were features of the suggested model. Their findings strongly correlate with both alternative heat transport models and experimental data. After the thermal characteristics of the air inside the parabolic solar collector dryer was examined, it was found that the air at the collector's inlet warmed up by 9°C and then somewhat dropped before entering the drying chamber (Ouedraogo et al., 2021). A thermal analysis of the SPTC dryer is essential to understand the thermal behaviour and performance during the drying process. Therefore, this paper aims to examine the heat transfer developed in the fabricated concentrated-type solar dryer and determine the heat transfer coefficient for solar drying of the ginger.

2. MATERIAL AND METHOD

A drying chamber and a parabolic trough solar collector make up the concentrated solar drier. The stainless-steel parabolic trough (1190 x 450 x 300 mm) directs solar radiation onto an 18 mm-diameter water-carrying receiver tube pipe. The pipe was positioned throughout the whole parabolic trough, at its centre. The flexile, heat-resistant cross-linked polyethene pipe (PEX) was used to join the pipe to the drying chamber's copper radiator tubes, which were 1300 x 410 x 400 mm. The water flow was provided by a straightforward syphon tank that was big enough to give enough of time for testing. A picture of the concentrated solar dryer is shown in Figure 2.

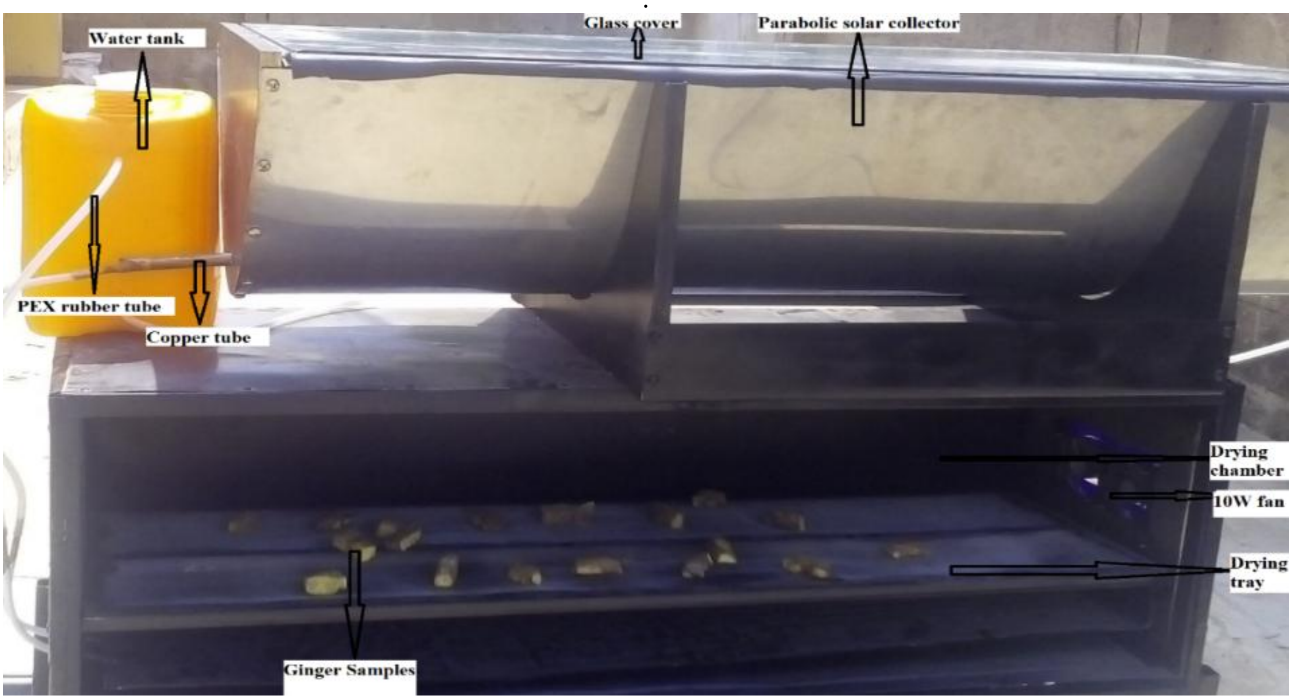

Figure 2. *Pictorial view of the Experimental setup*

To minimize heat loss from convection from the heat tube and provide the desired glazing appearance, an 8mm thick glass cover was placed over the parabolic trough solar collector. To absorb the heat required for the drying of the ginger, the interior of the drying chamber was painted black. In order to reduce heat loss, fiberglass lagged the drying chamber. Copper tubes in the drying chamber allowed the heated water in the tube air in the collector to return to the tank. To force convection and circulate heat from these copper tubes to the ginger, a fan is coupled to a ten-watt solar panel. Five kilograms of precisely weighed ginger samples were equally divided on the dryer's rectangular wire mesh trays (1150 x 335 x 10 mm), and an additional five kilograms of ginger samples were put on the open-air tray. The samples were weighed using a weighing scale balance at one-hour intervals, and the weight reduction figures were noted. A digital hygrometer was used to measure the relative humidity in the drying chamber and its surroundings. Thermocouples at the water entry and exit of the heat receiving tube and the drying chamber were used to measure the air temperature.

2.1. Heat Transfer Analysis

Heat transfer is essential for analyzing the thermal behavior of heat transfer in fluids (water and air) in the concentrated-type solar dryer. The thermal analysis considered the transmission of heat delivered by the concentrating solar collector, the convective heat transfer with the HTF, and the heat transfer within the drying chamber. The following formula provides the radiative heat exchange rate to a concentrating solar collector's focus point:

$$\dot{Q}_{col} = \eta_{col} A_{col} G_i \quad (1)$$

Where η_{col} signifies the collector's efficiency, A_{col} signifies the collector's area, and G_i is the collector's solar incident radiation.

The parabolic trough collectors consist of reflectors that are curved around an axis in a linear parabolic shape. Around a single focus line that is placed where a lengthy receiver pipe is supposed to heat the heat exchange fluid, they collect parallel rays. One method of heat transport is convection. It includes the heat transfer fluid (HTF) and the annulus between the absorber and receiver (de Oliveira Siqueira et al., 2014; Alimohammadi et al., 2020).

$$\dot{Q}'_{Receiver} = hD\pi(T_{hot} - T_{cold}) \tag{2}$$

But,

$$h = Nuk/D \tag{3}$$

Under laminar conditions, the HTF convection is determined by the Nusselt number; in the case of laminar flow inside the tube (where the Reynolds number is less than 2300), the mean Nusselt number is provided by equation (4) (Plappally & Lienhard, 2012):

$$Nu_{mean} = 3.66 + \frac{0.0668 \times Re \times Pr \times D_{ri}/L}{1 + 0.04(Re \times Pr \times \frac{D_{ri}}{L})^{2/3}} \tag{4}$$

Where Pr denotes the Prandtl number, D_{ri} denotes inner receiver diameter, Re denotes the Reynolds number, and L denotes the tube length. Equation (4) assumes an isothermal tube, a close estimate used in this study.

A forced convection drying scheme was related as an excellent method for quicker drying as the convective heat transfer coefficient associated with it is greater than natural convection drying (Sansaniwal & Kumar, 2015). Therefore, forced convection influenced the heat exchange in the drying chamber. The drying chamber's (DC) heat transfer is given in equation (5) (Lienhard & Lienhard, 2002).

$$\dot{Q}_{DC} = hA_{DC}(T_{hot} - T_{cold}) \tag{5}$$

But,

$$h_{DC} = Nu_L k/L \tag{6}$$

The convective heat transfer in the DC is of forced convection, which depends on the Nusselt number in turbulent conditions; the mean Nusselt number for this condition is as shown in Equation (7), from the work of Sansaniwal and Kumar (2015):

$$\overline{Nu}_L = 0.0370 Re_L^{0.8} Pr^{0.43} \tag{7}$$

Equation (8) was used to determine the amount of heat required to evaporate the moisture (Gyawali et al., 2022).

$$Q_{evap} = \mathrm{M_w} \times \mathrm{h_{fg}} \tag{8}$$

Where Q_{evap} signifies the required heat energy for the drying process (kJ), h_{fg} signifies the Latent heat of vaporization (kJ/kg H_2O).

The latent heat of vaporization used for this study is given by Equation (9) (Youcef-Ali et al., 2001)

$$h_{fg} = c_{pw} \times (597 - 0.56T_{DC}) \tag{9}$$

Where, c_{pw} connotes the water's specific heat capacity and T_{DC} connotes the temperature in the DC.

Equation (10) gives the mass of moisture (Mw) to be removed (Rulazi et al., 2023).

$$M_W = \frac{M_p(M_i - M_f)}{100 - M_f} \tag{10}$$

Where M_p connotes the ginger samples' mass before drying (kg), M_i connotes the initial moisture content of the ginger sample (w.b %), M_f connotes the final moisture content of the ginger sample (w.b %).

The parameters considered for the heat transfer analysis of the concentrating solar dryer in this study is displayed in Table 1.

Table 1: *Parameters for the dryer's heat transfer investigation*

Parameters	Symbol	Value	Unit
Reciever Tube			
Incident Solar Radiation	I	396	W/m^2
Extraterrestrial Radiation	G_{ext}	1661	W/m^2
Area of Parabolic trough	A_p	0.09	m^2
Collector thermal Efficiency	η	30	%
Receiver Diameter	D_{ri}	0.018	m^2
Nusselt number (flow in tube)	Nu	38.79	
Prandtl number	Pr	3.3	
Reynold's number	Re	6621	
Thermal conductivity (water)	k	0.63688	W/m.K
heat transfer coefficient (Reciever)	h	1372.48	W/m^{2}K
Drying Chamber			
Area of Dryer	A_D	0.533	m^2
Quantity of moisture to be evaporated	M_w	4.22	kg
Water's Specific heat	c_p	4.18×10^3	J/kg.^{o}C
Prandtl Number	Pr	0.708	
Air mass flow rate	m	1.085	kg/m^3
Average Velocity of air	U_{av}	1.73	m/s
Reynolds number	Re	123857.3	
Mean Nusselt number	Nu_{mean}	378.5	
Thermal conductivity (air)	k	0.027964	W/m.K
heat transfer coefficient (air)	h	17596.15	

3. RESULTS AND DISCUSSION

The model matches the trends of the experimental values, and the results obtained for the dryer's heat transmission are reported. From sunny February to March, temperatures were measured after 7 hours of drying with the concentrated solar dryer, and experimental data were acquired every 1 hour. The concentrated solar collector's focal point received 10.692W of heat transfer rate, which was then transported to the receiving tube. Table 2 shows the convective heat transmission to the HTF in the receiver tube. 1372.48 W/m.K was found to be the heat transfer coefficient (h_{Rec}) for the convective heat transfer process in the receiver tube.

Table 2: *Convective heat transfer rate for the receiver tube*

Drying Time	**T_{amb} (°C)**	**$T_{HTFentry}$ (°C)**	**T_{hot} (°C)**	**$T_{HTFexit}$ (°C)**	**$Q_{Reciever}$ (W)**
10:00	40	35	75	35	2715.0
11:00	42	37	79	73	5662.8
12:00	45	38	83	80	6205.8
13:00	46	43	89	82	6361.0
14:00	48	58	106	99	7679.7
15:00	48	65	113	113	8765.7
16:00	47	89	136	100	7757.3
17:00	45	72	117	92	7136.7

The forced air flow convection from the fan over the ginger samples influences the convective heat exchange in the drying chamber (DC). The results of the heat transmitted across the drying chamber are presented in Table 3. The coefficient of heat transfer h_{DC} for the convective heat transfer process in the drying chamber was got as 17.60 W/m.K.

Table 3: *Convective heat transfer rate for the drying chamber.*

Drying Time	T_{amb} (°C)	T_{hot} (°C)	T_{DC} (°C)	T_{DCexit} (°C)	Q_{DC} (W)
10:00	40	35	39	35	365771.2
11:00	42	73	49	52	459558.6
12:00	45	80	52	57	487694.9
13:00	46	82	55	60	515831.1
14:00	48	99	58	63	543967.4
15:00	48	113	59	78	553346.1
16:00	47	100	58	75	543967.4
17:00	45	92	57	66	534588.6

Figure 3 shows a thermal analysis of the high temperatures influencing heat transmission by the fluid in the dryer's drying chamber and receiver tube. The temperature in the receiver tube was always higher relative to the temperature in the drying chamber per hour due to the parabolic-cylindrical concentration at the receiver tube and the heat exchange between the receiver tube and the drying chamber. This conforms with the findings of Ouedraogo et al. (2021). However, an equilibrium temperature was established after 5 hours of drying, as observed in Figure 3.

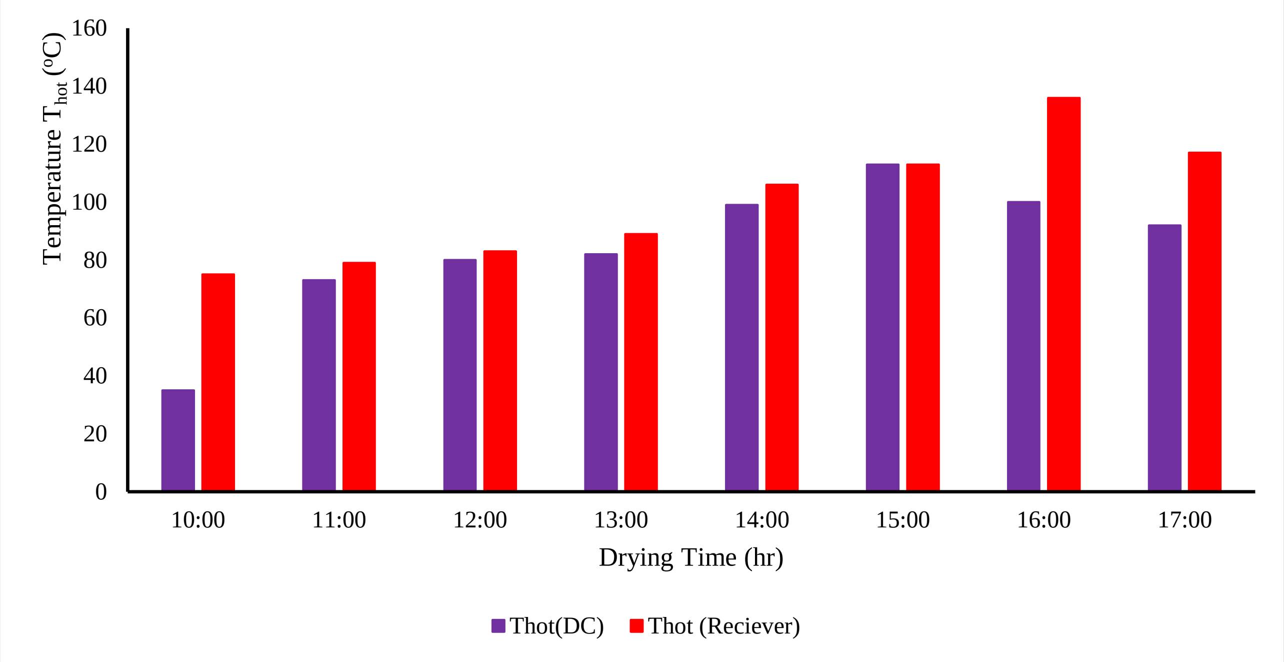

Figure 3. *Comparison of receiver temperature and drying chamber temperature per hour*

The convective heat transfer rate between the drying chamber and the receiver tube was also taken into account in the thermal study. As seen in Figure 4, there was a greater heat transfer rate per hour in the drying chamber as compared to the receiver tube. This may be explained by the dryer's increased thermal efficiency due to the drying chamber's airflow rate being higher than the receiver tube's HTF flow rate. This is in line with what Tagle-Salazar et al. (2018) reported.

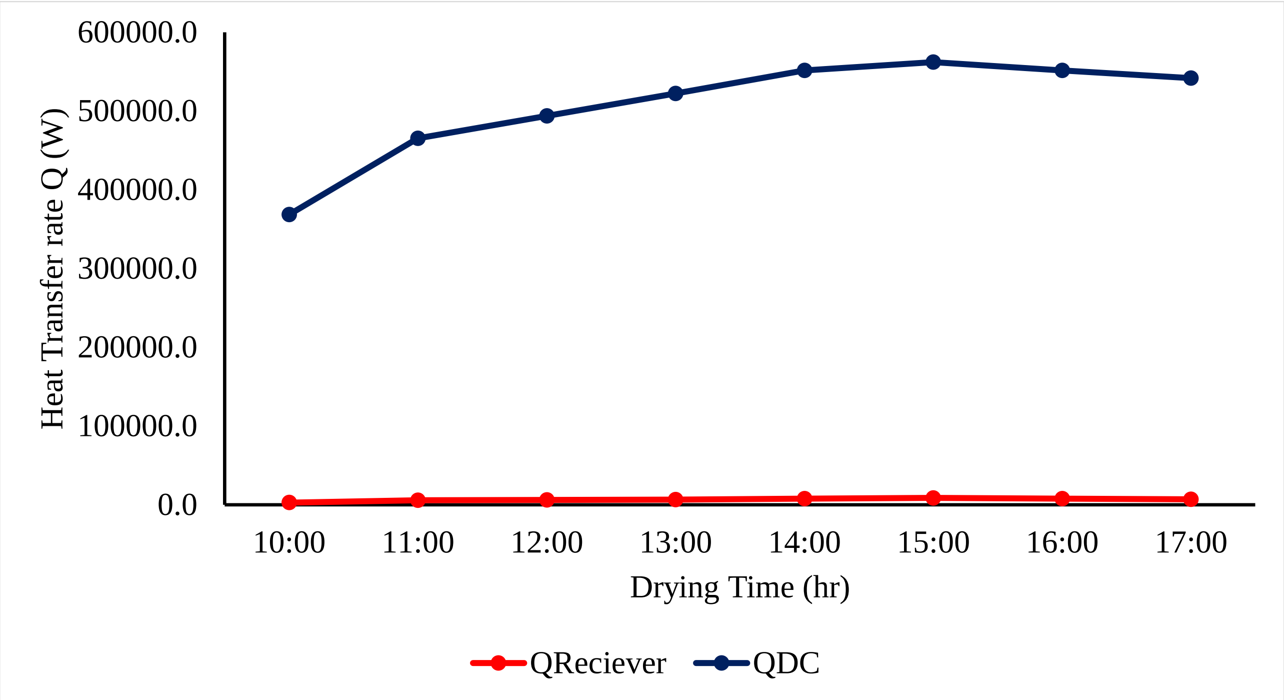

Figure 4. *Heat transfer rate in the receiver tube and drying chamber per hour*

As the drying temperature increased, the dryer's evaporative heat transfer rate dropped, as shown in Figure 5. This could be due to the reduction in the ginger sample's moisture content placed in the drying chamber. The lower the sample moisture content, the lower the dryer's evaporative heat transfer rate.

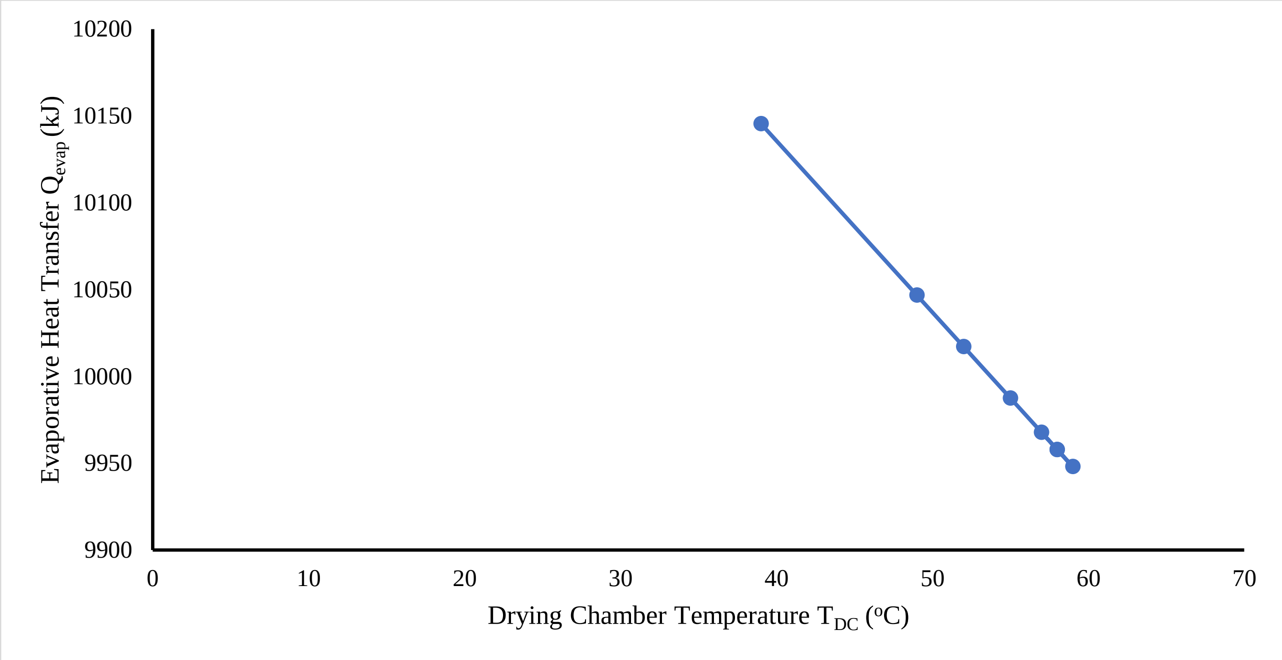

Figure 5. *Evaporative heat transfer rate in the drying chamber*

4. CONCLUSION

The solar parabolic trough collector (SPTC) dryer was used to dry 5kg of ginger samples, and the rates of heat transmitted in the receiver tube and the drying chamber (DC) and the heat transfer coefficients were examined in this study. The drying experiments were conducted within 7 hours on sunny days throughout February to March. The heat transfer rate delivered to the focus of the concentrating solar collector was 10.692W. Thermal analysis of the hot temperatures of the fluids in the dryer's receiver tube and drying chamber showed that the temperature in the receiver tube was always higher relative to the temperature in the drying chamber per hour. Thermal analysis of the convective heat transfer rate between the receiver tube and the drying chamber also showed a higher heat transfer rate per hour in the drying chamber relative to the receiver tube, thus enhancing the thermal efficiency of the dryer. The coefficients of heat transfer hRec and hDC for the convective heat transmission process in the receiver tube and the drying chamber were determined to be 1372.48W/m.K and 17.60W/m.K respectively. The thermal efficiency of the dryer was found to be 30%, a significant result that underscores the effectiveness of the SPTC dryer. The drying chamber's measured average temperature was 58.5oC, while the ambient temperature was 47.5oC between 15:00hrs and 16:00hrs. The ginger samples had a significant amount of moisture removed due to this notable +11oC temperature differential between the drying chamber and the surrounding air. In contrast to the 23.74% achieved by the open-air solar drying method, the ginger samples' final moisture content of 11.1% can be credited to the effective operation of the SPTC dryer. The design considered is simple and performed better in terms of lower final moisture contents, when compared with the work of Bhavsar and Patel (2023), that used both double air pass collector and phase change materials as thermal storage material, with a final moisture content record of 12.5%.

AUTHOR CONTRIBUTIONS

For the Conceptualization: Ige Bori, Methodology: Jonathan Yisa Jiya, Sunday Bako, Ige Bori, Supervision of fabrication process: Adamu Mohammed Orah, Jonathan Jiya, Muideen Oladele Oyebamiji, Performance evaluation: Ige Bori, Sunday Bako, Manuscript first draft: Adamu Mohammed Orah, Ige Bori, Manuscript review, editing and submission: Ige Bori.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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