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Design and Experimental Evaluation of a Fruits Hybrid-Solar Dryer

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Abstract: In this work a hybrid solar dryer is designed and its performance is experimentally evaluated. The user can set the drying parameters regarding the fruits to dry, and after the drying process started it can last a 12-hour drying cycle. It is designed to have maximum storage capacity of 10 kg. It can be configured to operate within the temperature range recommended for drying the product present. Two electrical sources (solar photovoltaic and conventional electricity) supplied the control system. This control system ensures the permanent presence of one of the two additional thermal sources (i e., the heating resistors and the energy gas). This makes it possible to obtain and maintain the recommended temperature range in the drying chamber. The simulation of the airflow distribution inside the device was performed with ANSYS Fluent software for the solar thermal mode and in case of an empty drying chamber. It showed that the drying-air is well distributed in the drying chamber and that the temperature inside the drying chamber is around 60°C. The performance tests, in a real environment (empty drying chamber and with loaded drying chamber), are used to validate the results of the simulations carried out and to assess the operation of the control system for a temperature range of 45 to 60°C. The maximum temperature reached in natural convection when the dryer is empty is 56.7°C. Tests made on pineapples slices showed that the dryer can reduce water from 80-86% to 6% in 12h. The use of this dryer will not only make it possible to carry out drying at any time of the day, but will also help to reduce the drying time of the products, while preserving their nutritional values.

Keywords: Hybrid Solar Dryer, Modelling, Simulation, Fruit Drying, ANSYS Fluent

1. Introduction

Food security is one of the world's most pressing concerns [1-4]. It is estimated that about a quarter of the population of Sub-Saharan Africa (SSA) is undernourished [5]. In Benin, according to the National Institute of Statistics and Demography (NISD), in August 2017, 42.9% of the population was estimated to be borderline food insecure, of which 9.6% was food insecure (80,000 people) [6].

Studies show that agricultural growth in Africa can be eleven times more effective in reducing extreme poverty than growth in other sectors [7]. This growth must undoubtedly correlate with the development of techniques for the conservation and processing of agricultural raw materials.

Indeed, post-harvest losses, particularly of fruit and vegetables, are enormous in sub-Saharan African countries every year. About 25% of cereal production is lost, compared to 50% for fruit and vegetables [8]. In addition, one third of food production is lost or wasted each year. Globally, this amounts to approximately US$750 billion of waste per year [9]. A report from the Belgian development agency's DEFIA project in Benin [10], states that Benin produces about

249,600 tonnes of pineapple waste per year.

During peak production periods, some highly perishable foodstuffs, particularly fruit and vegetables, require processing to transform them or extend their shelf life [11]. This is done through freezing, chemical treatment (salting) and drying. The purpose of these operations is to reduce the water activity available in a product or to limit the development of micro-organisms.

The solar drying applications are classified into three main categories, namely traditional, semi-traditional and industrial [12]. Crop drying is essential for conservation in agricultural applications [13]. This is done either by using fossil fuels in an artificial mechanical drying process or by placing the crop in direct sunlight with the consequences associated with this method of processing. The first method is expensive and has a negative impact on the environment, while the second method is totally dependent on the weather. In contrast, the use of a solar dryer is relatively cheaper, in terms of sustainability of the system, than these methods and more efficient [13].

Solar dryers of different sizes, capacities and designs are available for on-farm drying applications [14]. Some solar dryers operate without electricity or fossil fuels [13]. They are used for drying a wide variety of agricultural products, including fruit and vegetables. Unfortunately, solar dryers are limited. Their performance is highly dependent on climatic conditions (solar irradiance, ambient air temperature and relative humidity, ambient air velocity) [9, 11, 13]. The performance of solar dryers for agri-food products, for the most part, is negatively affected by the intermittency of the solar resource.

According to a recent study on solar dryer technologies, used for food applications [15], there is a huge technology gap between low-cost, energy-efficient dryer design and high-quality food production. Furthermore, given the need to develop sustainable food processing strategies for the future, these should not be limited to rural applications. Some aspects that need immediate attention are

1) For commercial applications, the quality of the dried product is an important criterion that determines the market value, explaining the requirement for efficient energy storage reserves with automated cut-off facilities to control the drying process [15];
2) Integration of computer applications for solar drying, through modelling, information and communication technologies (ICT) applications for supervision, control and automation [15];
3) Proper design and selection of solar dryer components is mandatory for efficient use of thermal energy. [15].

Different solar dryer technologies have been developed to address these perspectives. Hybrid solar dryers are legion [12, 13, 16]. The solar dryer developed by Nguimdo and Noumegnie [15] incorporates a thermal control system for drying tomatoes. Its performance has been shown to be better than that of a dryer without a thermal control system. However, this dryer only works with heating elements. On the other hand, the hybrid solar gas dryer developed by Zoukit et al. [17] not only has a unique design but also allows the use of gas burners that are automatically triggered according to the parameters entered by the user and the parameters measured in the drying chamber. But it is much more suitable for North African countries, due to the tilted angle of the solar collector, which allows a better connection to the drying chamber. Another hybrid photovoltaic dryers were recently designed and experimented by JB Hussein et al [18]. Effects of thermal insulation of solar dryer was discussed by Yaovi O. Azouma et al [19] for the drying of pineapples. [16]. Other researches were conducted on pineapples with indirect solar dryer [20-25]. Those researches show that there is a real need for more good and sustainable solar dryers. Many African countries, including Benin, are confronted with the problem of preserving agricultural products. The lack of effective long-term drying facilities is a major cause.

This work aims to provide solutions to the difficulties encountered by small and medium-sized enterprises (SMEs) in the region, particularly in Benin, specializing in the drying of agri-food products. It presents a new design for hybrid solar dryer for drying fruit and vegetables drying, with a thermal control system.

2. Material and Methods

2.1. Material

The design work was carried out using a laptop computer and two softwares. The first one is, the SOLIDWORKS software, which is used to make 3D models. The second software is ANSYS Fluent and it is used to simulate the temperature and relative humidity levels in the drying chamber of the solar dryer.

The materials used for the experiments are as follows:

1) The manufactured solar dryer;
2) An HTC-2 thermohygrometer with an accuracy of 0.1°C and 5% and a range of 70°C and 80% was used to measure the temperature and relative humidity outside the drying chamber;
3) A UNI-T UT 330A data logger with an accuracy of 0.5°C and a range of 80°C was also used to measure the temperature and relative humidity inside the drying chamber;
4) A PM 6252B pocket anemometer with a range of 30m/s, 60°C and 100% was used to measure the air velocity, temperature and relative humidity of the surrounding environment;
5) A temperature control system was used to maintain the temperature within the set range;
6) Three 100W heating elements;
7) A radiator fan was used to provide forced convection;
8) A 200Ah Sun Stone Power battery was used to power the control system.

The Figure 1 showed different experimental devices.

Figure 1. *Experimentation materials.*

Microsoft Excel program is used to produce the curves of the temperature and relative humidity in the drying chamber during the drying tests performed.

2.2. Methods

A bibliographical summary is used to select the type of hybrid solar dryer to be designed. Then, the materials to be used are chosen and the sizing of the dryer is carried out. The simulation of the physical model is then carried out with ANSYS Fluent software. The dryer is then built to verify the simulation results. The approach followed is summarised in Figure 2.

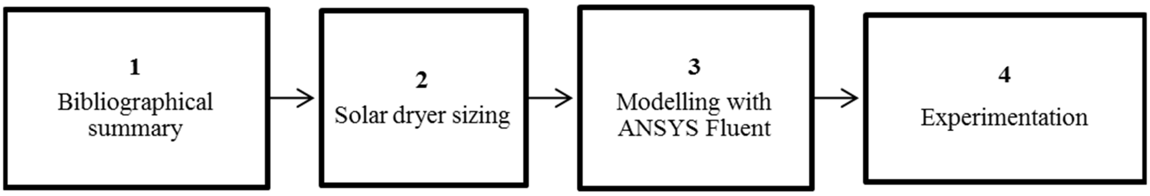

Figure 2. *Working method flow chart.*

2.2.1. Bibliographical Summary

Information on the drying properties of some fruits, the types of existing solar dryers and the performance indicators of these dryers is obtained from the cited literature of different authors who have worked on solar dryers. Various papers were also reviewed on the sizing method of solar dryers. An indirect solar dryer was selected from the literature review. The Figure 3 showed different components of the solar dryer.

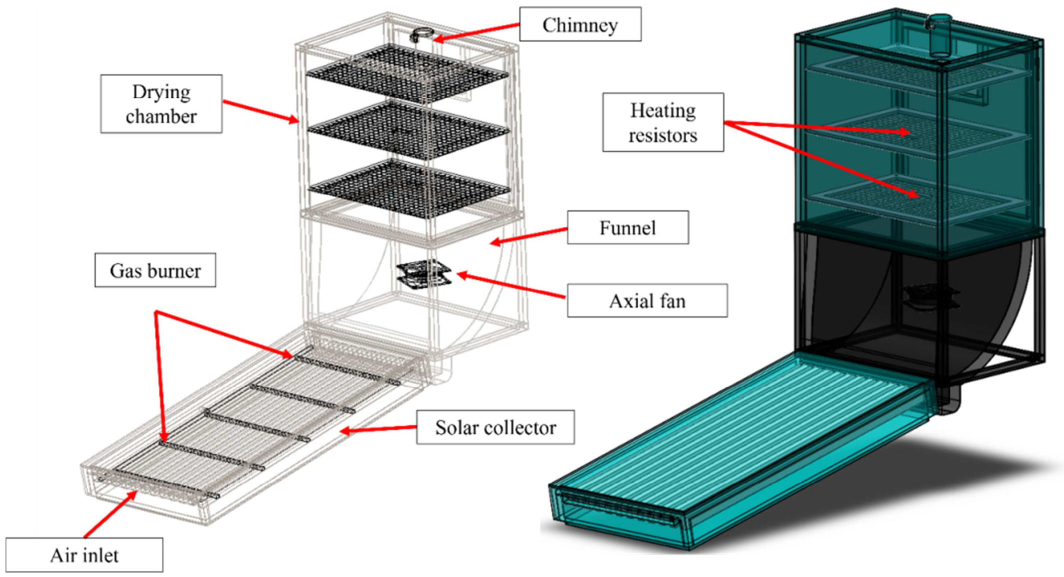

Figure 3. *Hybrid solar dryer.*

2.2.2. Description of the Dryer

The solar dryer designed is a hybrid indirect and automated type for drying fruits.

It consists of a drying chamber and a solar thermal collector that heats the air for drying the fruit in the drying chamber. An air circulation system powered by solar PV or conventional electricity is used. The automatic character of the dryer lies, among other things, in the fact that it is capable of autonomously triggering the ignition of the burners and/or the heating resistors depending on the drying parameters defined by the user and the parameters measured during the drying process. Figure 4 showed the dryer control logic. The device can be disassembled, allowing it to be moved from one place to another without much difficulty.

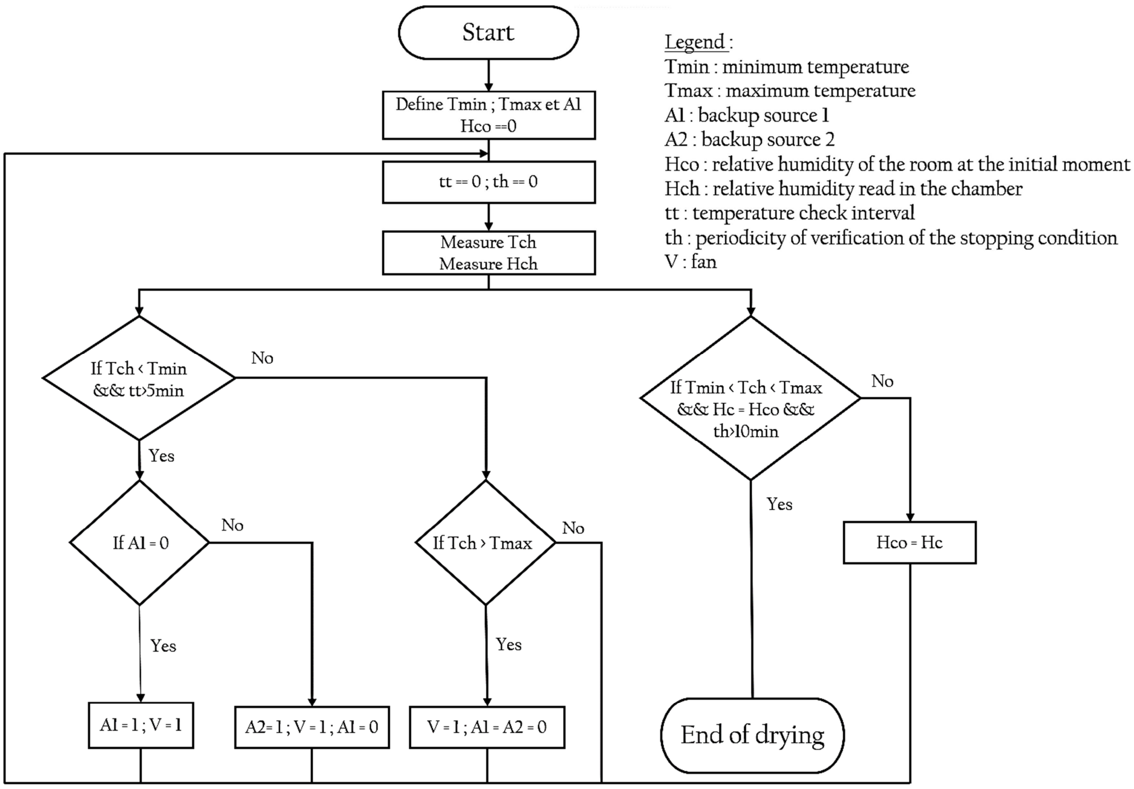

Figure 4. *Dryer control logic.*

2.2.3. Sizing of the Solar Dryer

The sizing of the dryer started with the knowledge of the quantity of the main product to be dried. This is 10kg of pineapple variety Cayenne Lisse produced in Benin. Next, the geographical characteristics and climatic conditions of the site where the dryer will be used must be known. This is the city of Cotonou, latitude 6.379448 and longitude 2.433333, the economic capital of Benin.

On the basis of these data, the initial and final characteristics of the product to be dried and the expected drying time, the average energy power required for the evaporation of the water contained in the product and the average air flow into the dryer are obtained. The average surface area of the absorber required can therefore be determined. These elements make it possible to choose the type of fan to be used and the dimensions of the solar collector.

The assumptions and specifications used for the design are presented in Table 1.

Table 1. *Requirements specification.*

Designations	Specifications and assumptions
Location	Cotonou (Latitude: 6.379448; Longitude: 2.433333)
Product	Pineapple (*Cayenne lisse*)
Harvest period	All year round
Quantity of fresh product	10kg
Initial water content of fresh product (wet basis)	80%
Recommended storage content (wet basis)	10%
Drying temperature	60°C
Ambient temperature	27°C
Ambient relative humidity	83%

Designations	Specifications and assumptions
Water activity of dried pineapple	0.5
Air flow rate in the drying chamber	67.01 m^3/h
Relative humidity of the air at the end of the drying process	50%
Average annual irradiation	4890 Wh/m^2/jr
Average solar irradiance	700 W/m²
Drying time	12h
Thermal efficiency of the solar collector	40% [17]

2.2.4. Simulation of the Physical Model Using ANSYS Fluent Software

The physical model of the dryer is represented using the ANSYS SpaceClaim drawing tool (Figure 5). This model is meshed (Figure 6) and the boundary conditions are then applied to it. The simulation is carried out using the Fluent tool in ANSYS.

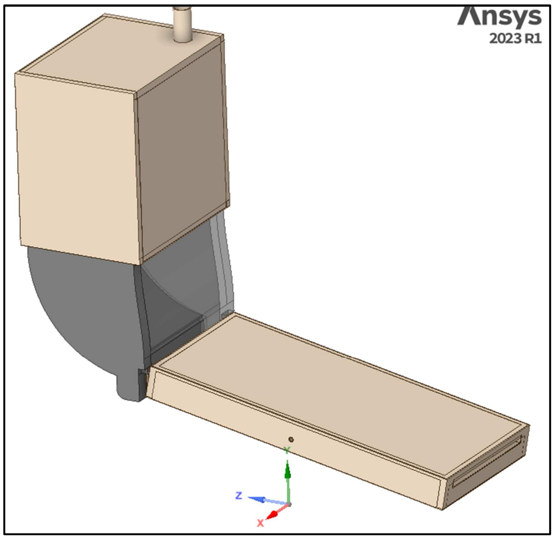

Figure 5. *3D simulation model.*

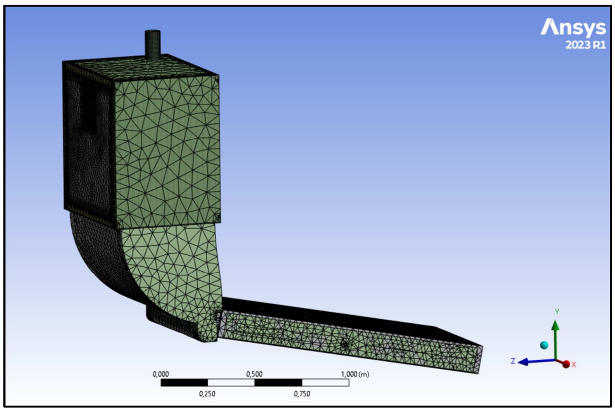

Figure 6. *Mesh geometry.*

The simulated boundary conditions are shown below:

Table 2. *Boundary conditions.*

Parameters	Values
Air inlet velocity (m/s)	2
Intake air temperature (°C)	27
Outlet pressure (Pa)	101325
Intake air humidity (%)	83

After the simulation, the temperature and relative humidity levels obtained can be visualised.

2.2.5. Experimental Evaluation of the Prototype Solar Dryer

The dryer is built with the dimensions retained after dimensioning. An empty chamber test is mainly carried out to verify the simulation results obtained. In addition, a pineapple drying test was carried out. For this test, pineapples were placed on two racks and a temperature sensor was placed near each rack. The bottom rack is "rack 1" and the middle rack "rack 2" (Figure 7). The pineapple was cut into slices of 5mm thickness each. For each run, there was 150g of pineapple.

Figure 7. *Arrangement of pineapple slices in the drying chamber.*

During the test, the control system is put on the door, to facilitate the interaction with the user and also to avoid damage to the electronic components due to the heat.

Table 3 summarises the tests carried out.

Table 3. *Summary of first experimental conditions.*

Experimental conditions	No-load test	Drying test
Date	27/12/2022	03/01/2023
Geographical coordinates	Long: E 2°26'33,15516", Lat: N 6°21'49,90104"	
Ambient temperature	26°C	27°C
Relative humidity of the ambient air	80%	80%
Average air speed in the solar collector (inlet)	2m/s	2m/s
Average irradiance	847 W/m²	740 W/m²

The values recorded were used to draw evolution curves with Excel software.

Three additional experiments were conducted in order to assess the effect on the air flow rate on the drying process. Below are the summary of the experimental conditions.

Table 4. *Summary of second experimental conditions.*

Experimental conditions	Parameters		
	Test 1	Test 2	Test 3
Type of test	Natural convection, without heating résistance	Forced convection, without heating résistance	Forced convection, with heating résistance
Date	13/03/2023	14/03/2023	15/03/2023
Geographic coordinates	Long: E 2°26'33,15516" Lat: N 6°21'49,90104"		
Ambient temperature	27°C	27°C	27°C
Average air entry speed into the solar collector	0.5m/s	0.5m/s	0.5m/s
Average irradiance	571 W/m²	621 W/m²	356 W/m²
Duration of the test	12h	12h	12h
Initial mass of fresh products	150g	150g	150g

150g of pineapples were also placed on the roof of the drying chamber, for drying in the open sun as shown in Figure 8. They will serve as control pineapple slices to assess the performance of the dryer.

Figure 8. *Control pineapple slices.*

3. Results and Analysis

3.1. Dryer Sizing Results

The results of the dryer's sizing are presented in Table 5.

Table 5. *Results of solar dryer dimensioning.*

Designation	Symbols	Values
Mass of water to be removed from the pineapple	m_e	7.78kg
Average rate of water removal from the product	V_m	0.65kg/h
Amount of water that can be removed from the product with one cubic meter of drying air	q_{eau}	9.7g/m³
Average air flow rate to be used in the dryer	$\dot{V}$	67.01 m³/h
Average energy required to evaporate the water contained in the product	P_u	0.79kW
Average collector absorber area (rectangular fin plate type)	S	2.82m²

The materials and dimensions of the dryer are shown in Table 6.

Table 6. *Materials and dimensions.*

Component	Material	Size
Solar collector absorber	Aluminum	1.5m * 0.68m, Thickness 1.5mm
Solar collector housing	Steel	1.5m * 0.74m * 0.15m, Thickness 1.5mm
Fins (air opening)	Steel	Thickness 1.5mm, Diameter 5cm
Transparent cover	Glass	1.5m* 0.72m, Thickness 4mm
Heat exchanger	Iron	1.5m*0.74m
Gas burner	Iron	Diameter 20 mm
Side insulation	Glass wool	Thickness 30mm
Bottom insulation	Glass wool	Thickness 30mm
Drying chamber		
Outer casing	Steel	0.8m * 0.8m * 0.6m, Thickness 2mm
Drying tray	Stainless steel cladding	Surface area 0.38 m²
Side insulation	Glass wool	Thickness 30mm
Bottom insulation	Glass wool	Thickness 30mm

The Figure 9 showed some details about the solar dryer.

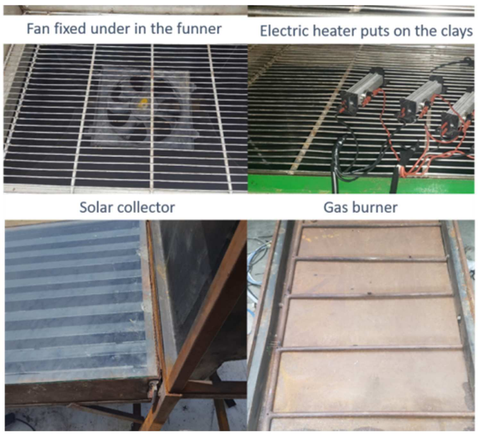

Figure 9. *Some details about the solar dryer.*

In the solar collector, the gas burner were placed under the solar absorber. Thus, the air in contact with the absorber will get heat given by the burner.

The electrical equipment required to operate the hybrid solar dryer is shown in Table 7.

Table 7. *Electrical equipments.*

Elements	Features
Fan	Voltage 12V, Power 80W
PV system with storage	Peak power: 623Wp, Battery capacity 200Ah C10
Heating resistor	300W

3.2. Simulation Results

The result obtained after simulation is shown in figure 10.

The analysis of this figure shows that the temperature in the solar collector is higher than that in the duct between the drying chamber and the solar collector. Specifically, the air temperature in the collector is higher than 60°C while the air temperature in the drying chamber is not at a uniform temperature. This result allows us to say that the dryer can effectively dry the products because it allows the fruit to reach the drying temperature. In fact, the Codex Alimentarius (WHO) recommends drying with heated air between 50 and 60°C.

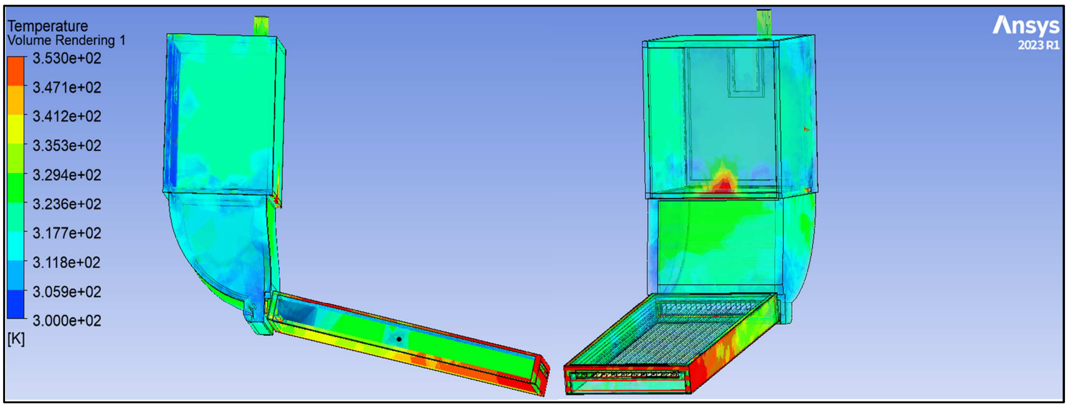

Figure 10. *Temperature distribution in the drying chamber.*

3.3. Experimental Results

3.3.1. No-Load Test

The Figure 11 shows the results obtained for the no-load performance test, in natural convection.

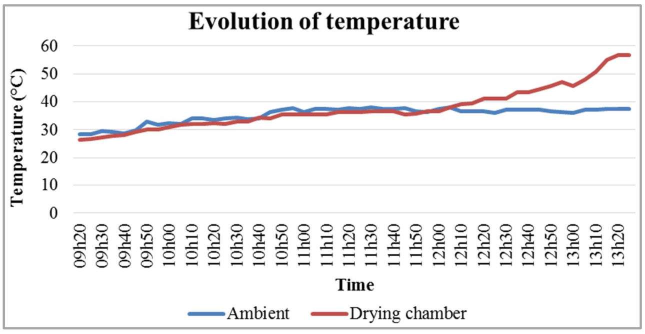

Figure 11. *Evolution of temperature during no load test.*

The analysis of the figure 11 reveals that the temperature of the ambient air remains almost stable around 35°C throughout the experiment. It should be noted that during the test, the ambient air temperature sensor was placed not far from the roof of the drying chamber, which could justify this temperature value obtained. Furthermore, the air temperature in the drying chamber increases gradually until it reaches the maximum value of 56.7°C after four hours of experimentation. This maximum value is close to the drying temperature of the fruit (60°C). There is also a large temperature difference between the temperature of the drying chamber and that of the surrounding environment at this time. This result shows that the temperature in the drying chamber is very high around noon, when the sun is generally at its zenith, similar results were reported for a small scale solar dryer [26] and for a village-level solar dryer for tomato under Savanna climate [27].

3.3.2. Drying Test

The figure 12 showed the temperatures of the ambient air and the air inside the drying chamber at two different locations.

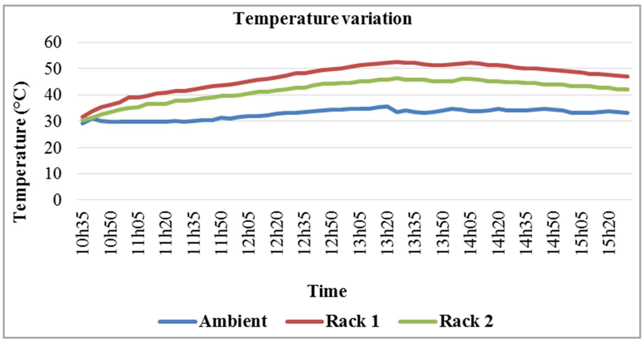

Figure 12. *Temperature variation during the drying test.*

The experiment is carried out with the control system. So the test is not carried out in natural convection only, forced convection has also been employed. Figure showed that the temperature of the place where the experiment is done, increased very little on the day of the experiment. In addition, it can be seen that the temperature curves on racks 1 and 2 do not merge but follow almost the same trend. More precisely, the temperature values on rack 1 are higher than those on rack 2 with a maximum of 52.7°C. This means that the temperature is not uniform at all points in the drying chamber. The shape of the funnel directly affects the well repartition of the temperature in the drying chamber. The variation in temperature at the entrance to the drying chamber has an effect on the temperature levels that can be reached in the chamber. The minimum temperature reached in the chamber is 30.3°C.

The Figure 13 showed the relative humidity of the ambient environment and at the two measurement points.

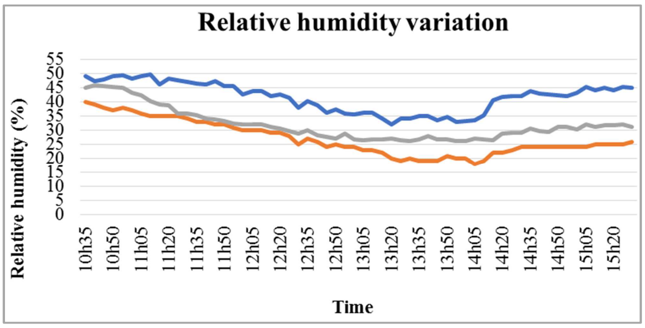

Figure 13. *Variation of the relative humidity during the drying test.*

The analysis of this curve showed that the relative humidity of the air in the drying chamber is lower than that of the ambient air. The relative air humidity curve measured at rack 1 falls below that of rack 2. This meant that when the air is circulated in the drying chamber, it takes water from the products on its way out. It can be seen that towards the end of the experiment, the curves for the relative humidity of the air in the chamber have the same shape as that for the humidity of the ambient air as stated in the review on indirect type solar dryers that drying parameters are directly related sunshine in real time [11].

The results of the second part of drying experimentation are presented below.

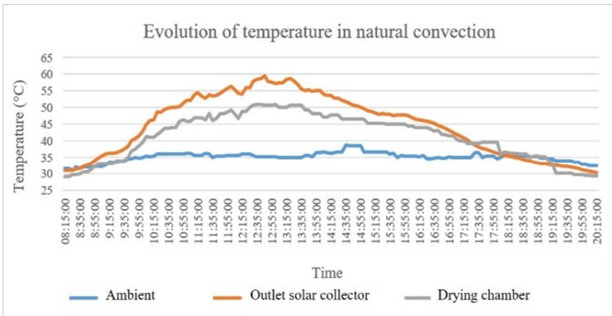

Figure 14. *Evolution of temperature during the test 1.*

The figure showed that the temperature curves at the solar collector outlet and at the bottom rack in the drying chamber follow almost the same pattern. More precisely, the maximum temperature reached at the exit of the solar collector (i e. in the funnel) is 59.5°C while that at the drying chamber is 51°C, i e. a temperature difference of 8.5°C. This temperature difference seems normal due to the presence of products which, by giving up their humidity to the air coming from the funnel, make it less hot. The minimum temperature reached in the chamber is 29.1°C. The temperature in the drying chamber at the end of the test is 29.3°C. The temperatures range inside the solar collector outlet was much higher than that inside the solar dryer chamber and ambient temperature during most hours of the daylight as observed by JB Hussein et al [18] in their experimentation.

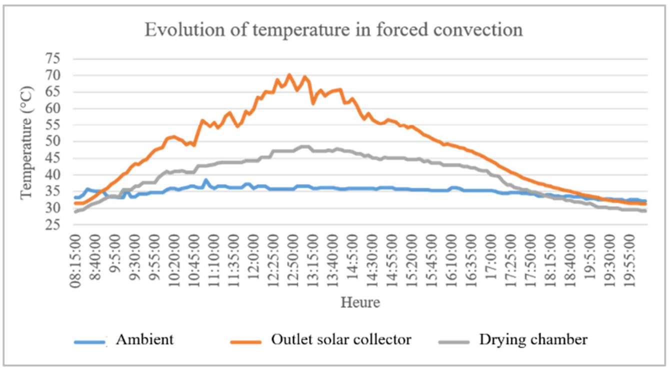

Figure 15. *Evolution of temperature during the test 2.*

Analysis of the figure revealed that the temperature of the ambient environment varies very little while that at the solar collector output increases significantly before gradually decreasing after 3 p. m. The temperature in the drying chamber underwent almost the same evolution as that read at the output of the solar sensor. But we see a large temperature differential between the temperature in the drying chamber and that at the outlet of the solar collector, especially between 10 a m. and 2:45 p. m. The maximum value reached at the sensor output is 70.1°C; the temperature value read in the drying chamber for this maximum value is 47.1°C, i e. a temperature differential of 23°C. It could be argued that the forced convection, regarding the position of the fan, contributed to a significant reduction in the temperature of the drying air.

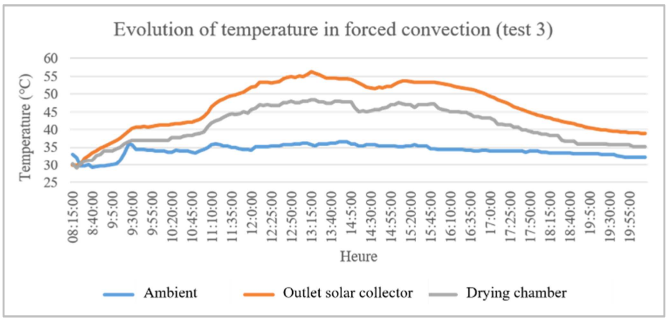

Figure 16. *Evolution of temperature during the test 3.*

It is noticed that the temperature curves at the sensor outlet and in the drying chamber follow almost the same pattern: a progressive increase until a maximum is reached and a decrease thereafter. The maximum temperature read at the output of the solar collector was 56.2°C and the temperature read in the drying chamber at the same time was 48.3°C, i e. a temperature differential of 7.9°C. This value is lower than the temperature differential of 23°C recorded during the forced convection test without heating resistance (test 2). This could be due to the presence of heating resistors in the drying chamber. The minimum temperature read in the drying chamber during this test is 29.1°C. The temperature reading in the drying chamber at the end of the test was 35.3°C. This last value is higher than those read during previous tests, due to the presence of heating resistors.

The table below is a summary of the results of three tests.

Table 8. *Summary of the results of three tests.*

Results	Test 1	Test 2	Test 3
Final water mass (g)	7	26	33
Final water content (%)	6	22	28
Mass of water extracted from the product (g)	118.14	111.70	108.62
Relative quantity of water extracted (%)	94	78	73
Drying speed (g/h)	9.84	9.31	9.05
Drying speed (%/h)	8	7	6
Average amount of water removed during drying (en g/m^3)	5.72	6.24	9.36
Average drying flow (m^3/h)	1,72	1,49	0,97
Air mass flow (kg/s)	0.027	0.026	0.027
Evaporative power of the dryer (kg/s)	0,152	0,158	0,25
Energy supplied by the solar collector (W)	2984.43	3897/19	3816.15
Solar collector performance (%)	23	27	46

Based on the final water content of the dried products, better drying performance is observed in natural convection. In fact, the drying speed of the products is higher (9.84 g/h) in the context of natural convection drying. The evaporative power of the dryer did not vary too much during the tests in natural convection (0.152 kg/s) and forced convection (0.158 kg/s). But it increased during the forced convection test with the heating resistors (0.25 kg/s). We could therefore say that the heating elements improve the evaporative power of the dryer. It could also be said that the current position of the fan does not promote good air circulation inside the dryer during the drying process. Indeed, it was noticed at the end of the forced convection tests that the fan is a little hot. It absorbs not only the heat leaving the solar collector but also that radiated by the heating resistors. The position of the fan should therefore be reviewed to ensure better air circulation inside the dryer. In fact, a recent research [22] showed that an active indirect solar dryer got better results than a passive one for the drying of pineapples.

Table 9 showed the data about the mass of pineapple slices at the end of the tests.

Table 9. *Mass of pineapple slices at the end of the tests.*

Mass of pineapple slices at the end of the tests (g)	Test 1	Test 2	Test 3
In the dryer	37	56	63
Control	42	37	75

The mass of the pineapple slices in the dryer is lower than that of the control pineapple slices at the end of tests 1 and 3. Drying products with the indirect dryer is better than that carried out in the open sun as showed by JB Hussein et al [18] because it reduces the drying time.

4. Conclusion

In this study, a prototype indirect solar dryer for fruit drying is designed and its performance is evaluated. The dimensioning of the dryer then carried out by considering the climatic conditions of the city of Cotonou and by supposing that it makes it possible to carry out the drying of 10kg of pineapples in 12h. It was found that the forced convection is important in the device. The simulation of the air flow distribution inside the dryer for an operation in solar mode and no load conditions is carried out and revealed a temperature below 60°C in the drying chamber. No load test confirm this result, temperature inside the drying chamber reaches 56.7°C.

Twelve hours drying experiments were carried out on 150g of pineapples and showed that drying products with the dryer is better than open sun drying. However, the position of the fan should be reviewed in order to ensure proper circulation of air in the dryer. So that the effect of the air flow rate (proper forced convection) can be assess.

It should be noted that there are many possibilities for improving the dryer. Experimentation must therefore be continued to control the performance of the dryer as well as possible.

In terms of perspectives for this study, the following task can be listed:

1) Know the efficiency of the solar collector and the evaporative capacity of the dryer;
2) Change the position of the fan and assess the effect of air flow rate in the drying process;
3) Carry out drying tests on other fruits than pineapple under different conditions to know the drying kinetics of these products by the dryer;
4) Improve the control system to make the dryer more efficient;
5) Use thermal storage materials to improve the thermal efficiency of the dryer.

List of Acronyms and Abbreviations

ICT: Information and Communication Technologies
NISD: National Institute of Statistics and Demography
SMEs: Small and Medium-sized Enterprises
WHO: World Health Organization

Nomenclature

Symbol	Designation	Unit of measurement
m_e	Mass of water to be removed from the pineapple	kg
V_m	Average rate of water removal from the product	kg/h
q_{eau}	Amount of water that can be removed from the product with one cubic meter of drying air	g/m^3
$\dot{V}$	Average air flow rate to be used in the dryer	m^3/h
P_u	Average energy required to evaporate the water contained in the product	kW
S	Average collector absorber area	m^2

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