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Design and Construction of a Mixed-Mode Natural Convection Solar Dryer for Mango Slices

Abdulai Karimu*, Abdul-Razak Osman, Clement Ayariga, Iddrisu Yahaya

Department of Agricultural Engineering, School of Engineering, University for Development Studies, Tamale, Ghana

**Corresponding Author's Email: akarimu@uds.edu.gh*

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ABSTRACT

Fruits like mangoes are produced in large quantities during the peak season, and high postharvest losses occur due to lack of appropriate storage and handling structures. The main goal of this study was to design and construct a mixed-mode natural convection (MMNC) solar dryer for drying of mango slices. The dryer was designed using AutoCAD and constructed with wood and glass using basic woodworking tools and processes. The developed dryer has a direct collector, a vertical collector, and an indirect collector. The drying chamber has two removable frames with 5 shelves each, a total drying area of 2.54 m^2 and a capacity of 10 kg of mango slices per batch. The dryer is fitted with caster wheels for easy turning and positioning. Test conducted with 940 g of fresh mango slices resulted in effective drying after 17 hours, from a moisture content of approximately 90% (wb) reduced to 17% (wb). The drying rate was found to be 4.3%/hr. The maximum temperature obtained in the drying chamber was 54.3 ℃ at a maximum ambient temperature of 37.6 ℃. The average temperature-rise in the drying chamber compared to the ambient temperature was 11.5 ℃. The dryer is therefore recommended for use both domestically and by small-scale food processors since it is more hygienic and has proven to be more efficient than open-air sun drying.

INTRODUCTION

Mango (*Mangifera indica* L.) is a fruit crop that belongs to the family of Anacardiaceae (Todorov and Bogsan, 2016). The fruit is very delicious, has an exceptional flavour, and is highly nutritious. On average, the mango fruit is made up of 60-75% flesh; 14-22% seed and 11-18% peel, depending on the cultivar (Mitra *et al.*, 2010). According to Mukerjee (1953), mango originated in Sri Lanka and India. In Ghana, the commercial varieties of mangoes grown include Julie, Erwing, Palmer Keith, Kent, Haden, and Spring Field (Okorley *et al.*, 2014). The fruit has good nutritional components and health benefits such as digestive health, immunity improvement, and eyesight improvement, among others. It is rich in Vitamin C, carotenoids, dietary fibre, potassium, magnesium, and calories, as well as antioxidants. Mango fruit can be processed into chips, ice creams, jams, and juices (Edusei *et al.*, 2022).

In Ghana, mangoes are abundantly produced during the peak season and about 40% usually go waste due to inappropriate storage and handling (Akurugu, 2011). Mango chips are a food product made from mango fruits. Its production involves cutting the fruit into slices and drying them. This process helps to extend the shelf life of the mango product. Open-air sun drying is the most common technique used for agricultural products in most developing countries. However, in this technique, the product is exposed to adverse weather conditions such as wind, rain, dust and insect infestations. This leads to a reduction in the economic value of the produce. The attempt to address these challenges led to the development of solar dryers, in which the product to be dried is enclosed in a chamber. Solar drying improves product quality compared to traditional open-air sun drying, hence enhancing the product's marketability.

Solar energy is abundant in Ghana, with solar irradiation being as high as 4-6 kWh/m²/day (Ahiataku-Togobo, 2016), yet maximum use is not made of this abundant resource. Several solar dryers have been developed over the years, to preserve agricultural products. However, the source of external energy some of these dryers require in their operation such as electricity, LPG and charcoal, either make them expensive to use or environmentally unfriendly. There is therefore the need for a solar dryer that is economical, environmentally friendly and easy to operate. The objective of this study was therefore to design and construct a mixed-mode natural convection (MMNC) Solar Dryer for mango slices in Northern Ghana.

MATERIALS AND METHODS

Study Area

The study was carried out at the University for Development Studies (UDS), Nyankpala Campus situated in the Northern Region of Ghana under the Tolon District. The district lies within latitude 9°25''N and longitude 0°58''W geographically. Nyankpala is 16 km away from the capital town of the Northern Region of Ghana with an altitude of 183 m above sea level. The monthly mean temperatures range from 25 – 38 ◦C in December and April respectively (Naabe *et al.*, 2021).

Design Requirements

The design was to be a batch dryer in terms of loading and unloading; it was to have a mixed mode heat supply, thus a combination of radiation and convection modes; its capacity was to be 10 kg; the dryer was to be affordable to the small-scale food processor, economical and convenient to operate by one person; the overall height should not be more than 2 m.

Conceptual Designs

In conformance with the standard design process, three (3) conceptual designs were developed. They are Integrated Design (Concept 1), Semi-Integrated Design (Concept 2), and Detachable Design (Concept 3). The main parts are direct, vertical and indirect collectors; air inlet and outlet; shelves, doors, and stands. The conceptual designs were evaluated using evaluation criteria based on general design parameters (i.e., cost of construction, ease of construction, ease of operation), in addition to a parameter specifically related to dryers (effectiveness of heat circulation). The parameters were assigned equal weights. Through a decision matrix, the Detachable Design (Concept 3) shown in Figure 1 was selected for further modelling using AutoCAD 2016 version.

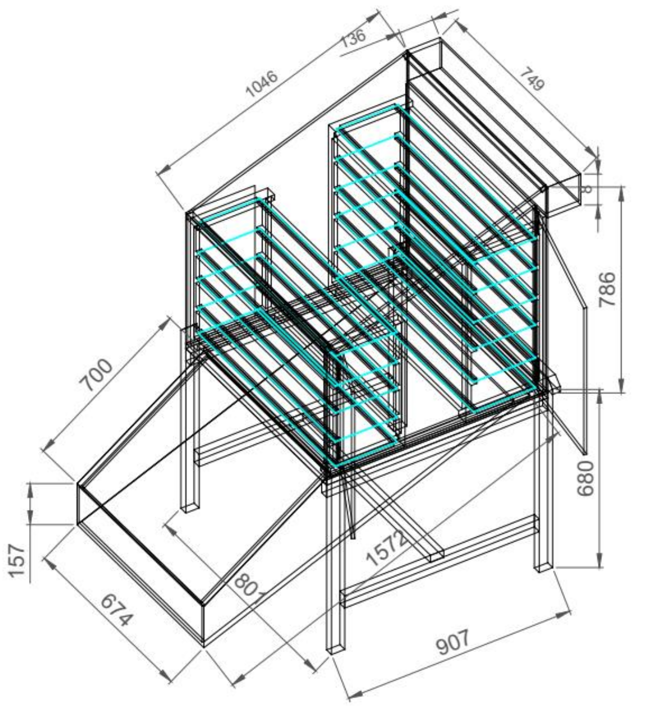

Figure 1: A detachable conceptual design of a MMNC solar dryer

Design Analysis

Areas of the solar energy collectors and shelves were calculated using Equation 1.

A= length × width ……………………… Eq. (1)

The volume of the drying chamber, V1 was determined by dividing it into a triangular prism (the top shape) and a rectangular prism (the bottom shape), and equations 3 and 4 respectively applied.

$V1 = 1/2 \times b \times l \times h$ …………………... Eq. (3)

$V2 = b \times l \times h$ ……….………………..…. Eq. (4)

Where b = base breadth, l = base length, and h = height of the prism

Materials Used

Materials used for the construction of the MMNC solar dryer were; a wooden frame, and plywood for the drying chamber with a 1 mm white Formica sheet inside lining for reflection and distribution of solar radiation. The solar energy collectors were made of 5mm transparent glass since glass allows solar energy into the drying chamber but does not allow heat energy to escape. Wood was used to frame the shelves. Others are fastening materials such as nails and glue, and then Caster wheels for easy turning and positioning. The air inlet and outlet were covered with a net to prevent insects from entering the drying chamber.

Construction of the solar dryer

The solar dryer design was put into sub-assemblies for easy construction. They were the housing, stand, and shelves sub-assemblies. The housing sub-assembly was made up of the drying chamber, collectors, an air inlet, an outlet, and doors. The housing sub-assembly is illustrated in Figure 2.

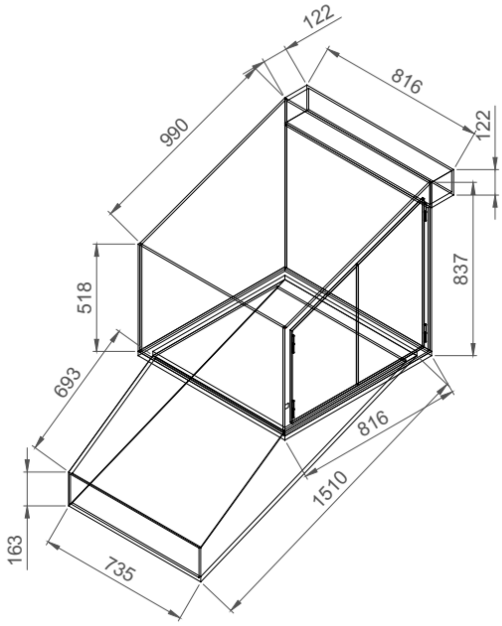

Figure 2: The housing sub-assembly

The Stand was constructed from 2 x 3 inches wood of 91 cm height with 4legs to keep the housing (drying chamber) at a convenient height for use. The housing stopper was fixed to prevent the housing from sliding back and also the whole stands were braced to keep it firm and stable. Caster wheels were fixed onto each leg of the stand to make it easy for turning and positioning. The stand sub-assembly is shown in Figure 3. Two (2) shelve stands were constructed from wooden frames, each shelf stands having 10 trays. The trays were made up of 5 mm thick glasses with an average spacing of 13.5 cm vertically. The shelves are designed to be removable for cleaning and loading. Figure 4 shows the shelf sub-assembly.

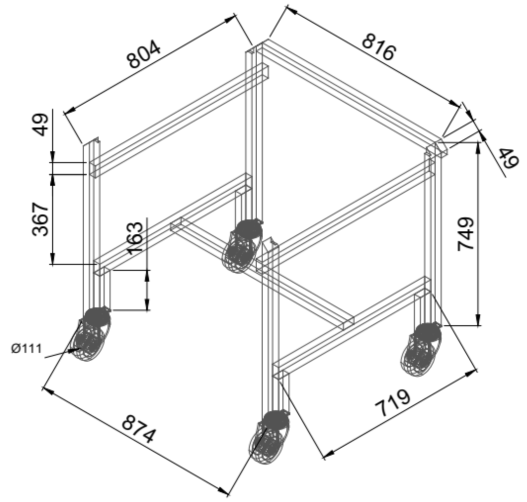

Figure 3: The stand sub-assembly

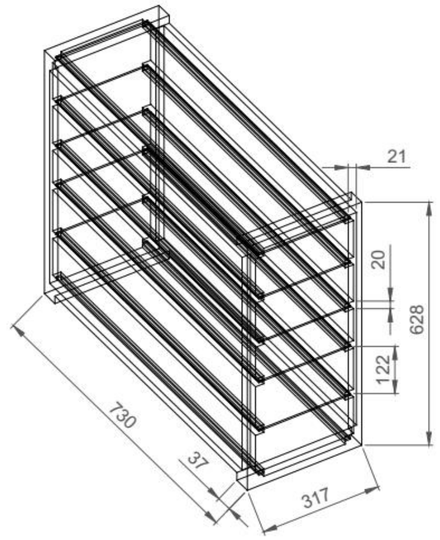

Figure 4: The shelves sub-assembly

Testing of the Dryer

After construction, the MMNC Solar Dryer was placed outside facing the sun. The drying chamber was loaded with 940g of mango slides with an average thickness of 5mm, well spread on each tray without overlapping. During the test-drying process, the ambient temperature, chamber temperature, and outlet and inlet temperatures were recorded. Also, the weight of the mango slides was measured in hourly intervals. The experiment lasted for three days.

The amount of moisture removed (M_r) during the testing was calculated using Equation 8:

$Mr = Wo - W1$ ……………………. Eq. 8:

Where: W_o = initial weigh, and W_1 = final weight

The percentage of moisture removed ($M_r\%$) from the mango slices was determined using Equation 9:

$M_r\% = \frac{wet\ weight - dry\ weight}{\text{wet weight}} \times 100$ … Eq. 9

The drying rate (R) of the Solar Dryer was calculated using Equation 10:

$R = \frac{M_i - M_d}{t}$ ……………………….. Eq. 10

Where: M_i = mass of the sample before drying, M_d = mass of the sample after drying t = drying period.

The drying efficiency (E) of the MMNC solar dryer was calculated using Equation 11:

$E = \frac{M_w \times L}{I_c \times A_c \times t} \times 100$ ………………… Eq. 11

Where: M_w = Weight of moisture evaporated, L = Latent heat of evaporation of water t = Drying time.

Statistical Analysis

Data were processed using simple statistical techniques in Microsoft Excel (2016), such as the calculation of percentages, means and presented in the form of Tables and graphs.

RESULTS AND DISCUSSION

Solar Dryer Design

Based on the evaluation parameters and criteria, concept 3 was selected and modelled using AUTOCAD 2016 version. The design is made up of housing, solar radiation collectors, shelves and a stand. Figure 5 presents a pictorial view of the designed MMNC solar dryer design.

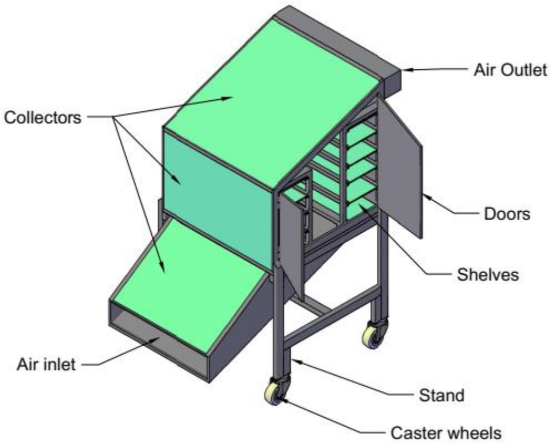

Figure 5: A pictorial view of the MMNC solar dryer design

Design Analysis

After completing the Solar Dryer design, the results of the engineering calculations showed that the direct, vertical, and indirect collectors were designed to have surface areas of 0.94 m^2, 0.58 m^2, and 0.51 m^2 respectively. Hence the total collector area was 2.03 m^2. The vertical collector has less effect on solar radiation; hence the total area of the effective collectors was 1.45 m^2. Two shelves were designed to have 5 trays each, which gives us 10 trays in total and each tray has an area of 0.254 m^2. Therefore, the total area for both shelves was calculated to be 2.54 m^2.

Design Calculations

Area of the direct collector, (A_1), $A_1 = lenght \times width$

Length = 0.97 m, and width = 0.97 m

$A_1 = 0.97 \times 0.97$

$A_1 = 0.94\ m^2$

Area of the vertical collector, (A_2), $A_2 = lenght \times width$

Length = 0.97 m, and width = 0.60 m

$A_2 = 0.97 \times 0.60$

$A_2 = 0.58\ m^2$

Area of the indirect collector, (A_3), $A_3 = lenght \times width$

Length = 0.79 m, and width = 0.64 m

$A_3 = 0.79 \times 0.64 = 51m^2$

Total Area of the collectors, $AT = A1 + A2 + A3$

$A_T = 0.94 + 0.58 + 0.51 = 2.03\ m^2$

Hence, the total area of the solar collectors is 2.03 m^2.

Drying chamber

The volume of the drying chamber, V

The volume of the triangular prism, $V_1 = \frac{1}{2} \times b \times h \times l$

Base(b) = 1 m, height (h) = 0.365 m and length (l) = 1 m

$V_1 = \frac{1}{2} \times 1 \times 0.365 \times 1 = 0.1825\ m^3$

The volume of the rectangular prism, $V_2 = b \times h \times l$

Where, b = 1 m, h = 0.635 m l = 1 m

$V_2 = 1 \times 0.635 \times 1 = 0.635\ m^3$

The total volume of the drying chamber, $V_T = V_1 + V_2$

$V_T = 0.1825 + 0.635 = 0.818\ m^3$

Therefore, the total volume of the drying chamber is 0.818 m^3

Shelves

Area of Trays, A (single tray), $A = lenght \times width$

$A = 0.873 \times 0.292$

$A = 0.254\ m^2$

The total area of the 10 trays, $A_T = 0.254 \times 10 = 2.54\ m^2$

Hence, the total area of the drying space is 2.54 m^2.

Detail Drawing of Mixed-Mode Natural Convection Solar Dryer

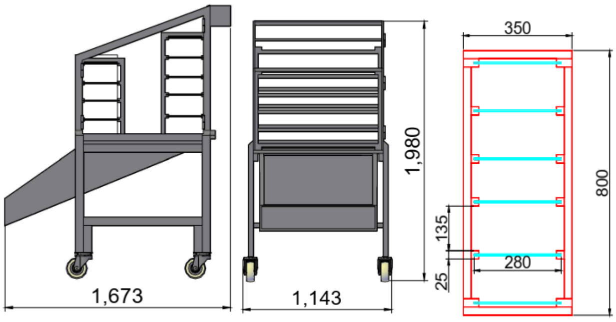

Figure 6a. Detail Drawing of MMNC Solar dryer (mm)

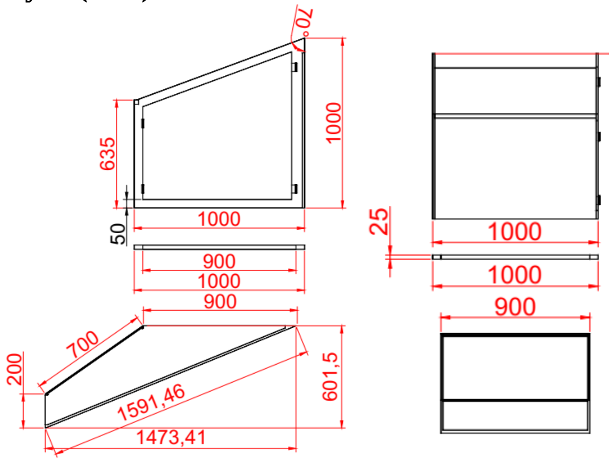

Figure 6b. Detail Drawing of MMNC Solar dryer (mm)

Construction of the MMNC Solar Dryer

After the design, the dryer was successfully constructed using locally available materials from the Tamale timber market. The constructed MMNC solar dryer comprises the housing sub-assembly, the stand sub-assembly, and the shelves sub-assembly. Pictures of the constructed MMNC solar Dryer are shown in Figure 7. The constructed dryer conformed to the stated design requirements.

Figure 7. Pictures of the constructed MMNC Solar Dryer (a) Doors closed (b) Doors closed

Testing Results

The results of the performance testing of the MMNC Solar Dryer, carried out for three (3) days in September 2021, at the Engineering workshop of the University for Development Studies (UDS) Tamale, Ghana, are presented in Tables 1 to 4. The appearance of the mango slices as the moisture was removed is shown in Figure 8.

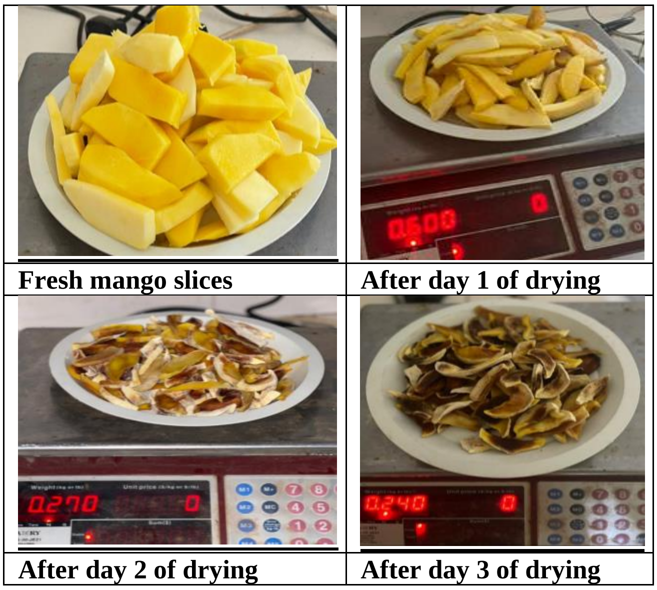

Figure 8. Appearance of the mango slices as the moisture was removed

Table 1: Variations of the Ambient and drying chamber temperatures at Day 1

Time	Ambient temperature (°C)	Chamber temperature (°C)
1 pm	36.7	53
2 pm	32.7	47
3 pm	37.6	54.3
4 pm	33.5	49.3
5 pm	32	40.5

Table 2: Variations of the Ambient and drying chamber temperatures at Day 2

Time	Ambient temperature (°C)	Chamber temperature (°C)
10 am	32	40
11 am	33.9	44.8
12 pm	34	47.6
1 pm	36.5	48
2 pm	33.6	43.7
3 pm	34.7	45.3
4 pm	33	43
5 pm	32.2	41.8

Table 3: Variations of the Ambient and drying chamber temperatures at Day 3

Time	Ambient temperature (°C)	Chamber temperature (°C)
10 am	29.6	38.5
11 am	32	40.6
12 pm	30.8	39.4
1 pm	34	46.6
2 pm	33.6	44.2
3 pm	31.5	39.5

Table 4: Moisture content of the various drying days

Days	Mass (g)
Initial	940
1	540
2	210
3	180

Discussion of Test Results

In Tables 1- 3, the average highest temperature in the drying chamber was found to be 45.2 °C and the average highest ambient temperature recorded was 33.4 °C. This indicates that the rise in temperature of the dryer chamber was about 11.8 °C more as compared with the ambient temperature. These values are very similar to what was obtained by Tibebu (2015), which reported the average highest air temperature in a direct type forced air circulation solar dryer to be 45.1 °C and an ambient temperature of 34.6 °C with 10.5 °C rise in temperature of the dryer. Also, the rise in temperature of the MMNC solar dryer proves to be better than a constructed indirect-type Solar Dryer by (Forson *et al.*, 2007), which reported an average temperature rise of 6.9 degrees.

The maximum temperature of 54.3 degrees was obtained in the drying chamber and a maximum ambient temperature of 37.6 °C was also obtained. Siddiqui *et al.* (2021) obtained a similar maximum temperature of 50 degrees for an indirect-type solar dryer. The mass of the mango slices of 940 g was reduced to 180 g in the dryer during the testing period.

Temperature Variation and Drying Rate

Figures 8-10 represent the hourly variations in the ambient and the chamber temperatures according to the days of drying. The MMNC solar dryer does not give constant temperature against time due to variations in solar radiation during the day.

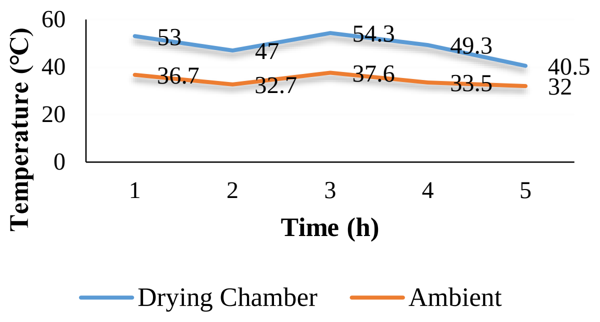

Figure 8. Variation of ambient and drying chamber temperatures with time at Day 1

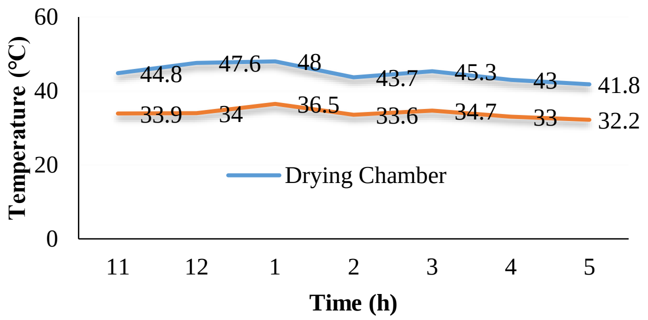

Figure 9. Variation of ambient and drying chamber temperatures with time at Day 2

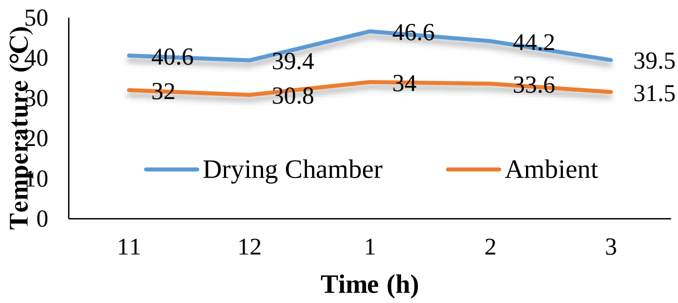

Figure 10. Variation of ambient and drying chamber temperatures with time at Day 3

Figure 10 shows the amount of moisture content differences between the mango slices to the drying time in the drying chamber. It is clear from the graph that; much moisture was lost from the mango slices by the MMNC solar dryer as the 940g of mango slices was reduced to 180 g within 17 hours. of drying. A passive direct-type solar dryer was constructed by (Akoy *et al*., 2006) who reported initial moisture content of 81.4 % of the material and final moisture of 10% in 2 days of drying time. The currently developed MMNC solar dryer achieved a similar final moisture content of 10% but with an initial moisture content of 90%. This indicates that the temperature inside the newly developed dryer chamber was higher.

CONCLUSION

A MMNC Solar Dryer having the potential of producing quality dried-out mango chips was successfully modelled in the AutoCAD 2016 version based on the evaluation parameters. It was constructed to conform with the design requirement, to help bring down post-harvest losses of mango fruits in the Northern region.

From the assessment, it can be concluded that, with an optimum drying chamber temperature of 54.3 °C recorded at an ambient temperature of 37.6 °C, the MMNC Solar Dryer can raise the ambient air temperature by 11.5 °C to dry items in its drying chamber faster than those placed in the open air. Also, with a batch mode of operation, the developed dryer is capable of removing 760 g of moisture within 17 hr., thus a drying rate of 0.045 kg/h.

CONFLICT OF INTEREST

The authors declared that there is no competing interest regarding the publication of this paper.

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