Performance Evaluation of a Forced Convection Mixed-Mode Solar Grain Dryer with a Preheater

Johannes P. Angula, Freddie Inambao

Abstract: In this study the performance of a forced convection mixed-mode solar grain dryer integrated with a preheater was evaluated. The type of grains used in the experiment were 72 freshly harvested maize cobs with a total mass of 17 kg. The experiment was conducted at various airflow speeds and preheater temperatures ranging from 0.5 m/s to 2 m/s and 30 °C to 40 °C, respectively. The aim of the study was to improve the performance of an existing indirect solar dryer which was converted to a mixed-mode solar dryer. The initial thermal efficiency of the indirect solar dryer before modification was 36 %. The results from the experiment indicated a maximum thermal efficiency of 58.8 % with a corresponding drying rate of 0.0438 kg/hr. The minimum thermal efficiency for the mixed-mode solar grain dryer system was 47.7 %, with a corresponding drying rate of 0.0356 kg/hr. The fastest drying time of maize cobs was achieved in 4 hours and 34 minutes from an initial moisture content of 24.7 % wb to 12.5 % wb. The findings show a significant improvement in the dryer system's performance. This is a clear indication that operating a solar dryer system in mixed-mode operation with forced convection and the assistance of a preheater or backup heater can significantly improve drying processes and increase food preservation.

Keywords*: *Mixed-mode operation, Solar drying, Maize cobs, Thermal efficiency, Preheater, Forced convection.

I. INTRODUCTION

The use of solar energy in agricultural applications such as solar grain dryers is widely accepted in many parts of the world as a green energy solution [1]. Solar drying of grains involves using solar thermal energy to remove moisture from grains in order to obtain a moisture level that is desirable for safe storage of the grains. According to Kenneth et al. [2], the storage temperature of grains and the amount of moisture in the grains can determine the maximum storage time without compromising on its quality. Research shows that maize grains can be safely stored and preserved for a long period if the level of moisture content is not more than 13 % wb [2], [3]. Maize is a family of grains, and grains are one of the healthiest foods and a primary source of carbohydrate consumed worldwide. Maize is a staple food in many parts of the world, particularly in underdeveloped and developing countries such as South Africa. In South Africa, maize is consumed by about 60 % of the country's population [4]. It forms part of a healthy diet of human beings and it is also served as a delicacy to animals. Research indicates that most maize farmers in South Africa, including subsistence farmers, rely on the open-air sun drying method for maize; a conventional drying method that leads to unfavorable outcomes [1]. In general, there are three types of solar drying techniques that can be used to dry crops; (i) direct solar drying, (ii) indirect solar drying, and (iii) mixed-mode solar drying. More details on the different types of solar drying techniques can be found in many available literature such as [5]–[8]. With the use of appropriate drying techniques such as using a forced convection mixed-mode solar dryer with a preheater or backup heater, the drying process can be significantly improved, particularly in high humidity areas such as coastal towns. This study was based on the operation principles of mixed-mode solar drying in which maize cobs were the subject of the drying process. This method uses a forced convection mixed-mode solar dryer which is integrated with a preheater for maximum performance. The solar dryer used for the experiment was a modification of an existing solar dryer developed by the Department of Mechanical Engineering at the University of KwaZulu-Natal, Durban, South Africa [9]. Initially, the solar dryer was designed as an indirect solar dryer system for drying faecal sludge. It was reported that this prototype solar dryer had a thermal efficiency of 36 % and was able to dry synthetic faecal sludge in 12 hours from an initial moisture content of 70 % wb to 20 % wb. Despite the longer drying time, it was also found that the solar collector could not heat air to a sufficiently high temperature due to the inconsistency of incident solar irradiation and the high humidity of the atmosphere. In order to improve the thermal performance and drying process for the existing indirect solar dryer system it was necessary to change its operation to mixed-mode. The main modification made was to incorporate a preheater and forced convection airflow in order to increase the drying rate. The aim of this study was to improve the performance of the solar dryer by increasing its thermal efficiency and drying rate.

II. RESEARCH SITE

The research was conducted at the University of KwaZulu-Natal, Howard College campus in Durban located at 29.9° South, 30.98° East, and at an elevation of 151.3 m above sea level. The city has a hot humid subtropical climate with temperatures ranging from as low as 9.4 °C in winter to as high as 30.8 °C in summer.

Manuscript received on November 26, 2020.
Revised Manuscript received on January 25, 2021.
Manuscript published on February 28, 2021.

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According to meteorological data from the Virginia weather station in Durban, the relative humidity of this coastal city can be as high as 95 %. Research indicates that the daily average sunlight hours in Durban is around 6 hours and 24 minutes per year.

The annual average values of Direct Normal Irradiance (DNI) and Global Horizontal Irradiance (GHI) are 1574 kWh/m2 and 1638 kWh/m2, respectively [10].

III. METHODOLOGY

A. Materials and Experiment Setup

To set up the experiment, the following materials were used for the experiment:

- A solar dryer system
- 72 fresh maize mealies (17 kg batch)
- A preheater/air heater
- PID temperature controller
- An RTD temperature sensor for the temperature controller
- Solid-state relay for the temperature controller
- Supply of compressed air through an air dryer
- A needle flow valve
- NI USB-6000 data logger
- Four temperature and humidity sensor probes
- Electrical wiring, piping and fittings
- Moisture meter
- Anemometer
- Laptop
- AC/DC voltage supply

Experimental data were measured using four positioned HTM2500LF sensor probes (denoted S1, S3, S4, and S5 in Fig. 1) and logged by a data logger for analytical purposes through the use of a laptop. The experiment was conducted for the same number of trials under the same temperature and airflow velocity conditions of the preheater as performed during the simulation. A few electrical modifications were made to the equipment, such as to employ a temperature controller on the preheater and rewiring of the heating elements to lower their amperage. This was done because, initially, the preheater did not have a temperature control circuit. The preheater temperature control circuit included a PID temperature controller, a solid-state relay (SSR), and an RTD temperature sensor probe (denoted S2 in Fig. 2). Fig. 2 shows the control layout schematic for the experimental setup, while Fig. 2 shows the complete experimental setup.

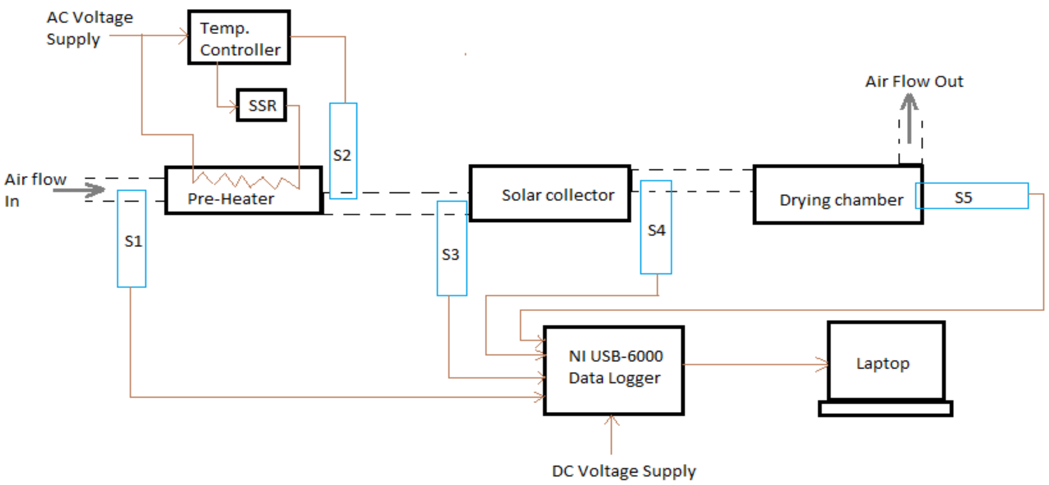

Fig. 1. Electrical control layout and connections of the solar dryer system

Fig. 2. Complete experimental setup of the solar dryer system

B. Experimental Procedures

Calibration of the sensors preceded the experimental procedures to ensure correct measurements were taken by each sensor positioned across the dryer system. The experimental procedures undertaken in this study were as follows:

a) Securely position one sensor probe at the preheater's inlet, one sensor probe at the solar collector outlet, another one at the inlet of the drying chamber, and the last one at the drying chamber outlet.
b) Prepare 8 maize cobs by removing the corn husks and measuring each maize cob's moisture content using the moisture meter. Average moisture content is used as the initial moisture content.
c) Through an air dryer, turn on the compressed air supply line.
d) With the use of a needle flow control valve and an anemometer, adjust the airflow to 0.5 m/s at the solar collector's inlet.
e) With the use of the temperature controller, set the temperature of the preheater to 30 °C.
f) Securely position 6 maize cobs in the drying chamber and the remaining 2 dehusked maize cobs on the open-sun drying tray.
g) Connect the USB cable from the NI USB-6000 data logger to the laptop and open the DAQ Express software application.
h) Once the software application opens, choose analogue inputs and add 8 input channels because there are two input signals (temperature and humidity) from each sensor probe.
i) On the software application window, change the sampling rate to 9 minutes (0.00185185 Hz) so that measurements are taken every 9 minutes.
j) Start recording the four sensor probes' readings until a final moisture content of less than 13 % wb is achieved.
k) While the laptop monitors and stores readings from the four sensors, use the moisture meter to keep measuring and recording the moisture content of maize cobs inside the drying chamber and in the open sun every 20 minutes (for the first 1-hour) then every after 15 minutes (after 1-hour drying).
l) Maintain the drying parameters until a moisture content safe for grain storage is achieved. The recommended moisture content for safe storage of grains is 13 % wb or less.
m) Once a moisture content of less than 13 % wb is achieved, repeat the above steps for the following drying parameters:

- Airflow at 0.5 m/s and preheater temperature of 35 °C.
- Airflow at 0.5 m/s and preheater temperature of 40 °C.
- Airflow at 1 m/s and preheater temperature of 30 °C.
- Airflow at 1 m/s and preheater temperature of 35 °C.
- Airflow at 1 m/s and preheater temperature of 40 °C.
- Airflow at 2 m/s and preheater temperature of 30 °C.
- Airflow at 2 m/s and preheater temperature of 35 °C.
- Airflow at 2 m/s and preheater temperature of 40 °C

n) Safely disconnect all electronic devices from the power supply and analyse the data.

The type of maize cobs and the moisture meter used in the experiment are shown in Fig. 3. For each experiment conducted, 8 maize cobs were used and tested for the right level of moisture content.

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Fig. 3. Sample maize cobs (left) and moisture meter (right) measuring the moisture content of one of the dehusked maize cobs

IV. RESULTS AND DISCUSSION

The entire experimental process was carried out in 11 days in the month of September and October (spring) that were chosen with good sunlight between 09h00 and 16h00. The first two days were used for the experimental setup and dry-run tests to ensure all equipment was functioning as needed, with the experiment being conducted on the remaining nine days. Based on the weather information, the data for Durban solar energy during the period of experiment indicated that the average daily incident solar irradiance was between 4.8 kWh/m^2 and 5.5 kWh/m^2 for September between 5.6 kWh/m^2 and 6.5 kWh/m^2 for October [11]. During the experiment, it was necessary to record the ambient weather temperature and relative humidity. Table 1 shows the minimum and maximum temperature and relative humidity values as recorded between 09h00 and 16h00.

The inconsistency of the weather patterns resulted in the fluctuation of atmospheric air temperature and relative humidity. As shown in Table 1, on some days the ambient temperature was as low as 16.4 °C and as high as 32.3 °C. Due to Durban's highly humid weather, the ambient relative humidity fluctuated between 46 % and 81 % during the experiment. The variation of temperature and relative humidity for drying air across the dryer system was measured by four HTML2500LF sensor probes. The results are presented and discussed in the following sub-sections. Each graph shows the minimum and maximum value recorded during that period.

Table 1. Ambient weather conditions during the period of the experiments

	Ambient Temperature		Ambient Relative humidity	
	Minimum Temperature (°C)	***Maximum Temperature (°C)***	***Minimum Relative Humidity (%)***	***Maximum Relative Humidity (%)***
Day 1	18,9	27,8	52	81
Day 2	20,1	31,6	42	76
Day 3	19,8	28,2	50	79
Day 4	21,6	32,3	46	65
Day 5	17,8	26,8	58	71
Day 6	18,1	29,3	57	80
Day 7	16,4	28,4	51	68
Day 8	19,4	32,1	46	70
Day 9	20,4	29,5	48	74

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B. Variation of Temperature and Relative Humidity Across the Dryer System

The analog output logged by the data logger from the sensors was in voltages and needed to be converted from voltage to temperature and relative humidity values. The following polynomial equations (1) and (2), available in the data sheet for the HTM2500LF sensor probes, were used for the conversion.

Relative Humidity:

$$RH\ (\%) = (-1.92 \times 10^{-9} \times V^3) + (1.44 \times 10^{-5} \times V^2) + (3.4 \times 10^{-3} \times V) - 12.4 \quad (1)$$

Temperature:

$$T(^{\circ}C) = (-2.428 \times 10^{-9} \times V^3) + (2 \times 10^{-5} \times V^2) - (7.419 \times 10^{-3} \times V) + 123.324 \quad (2)$$

Where V is the sensor output voltage in mV

results of these variations are shown in Fig. 4 and Fig 5

1) *Average Temperature and Relative Humidity at 30 °C Preheated Air*

The temperature of the weather in Durban is mostly below 30 °C, although in some cases, the temperature surpassed 30 °C. During the low-temperature periods, the air entering the solar collector was preheated to 30 °C. The variations in temperature and relative humidity as the air navigated through the solar dryer system from the preheater were measured and recorded. As measured by the sensors, the results of these variations are shown in Fig. 4 and Fig 5.

The figures in Fig. 4 and Fig. 5 indicate the results for the first 3 hours and 9 minutes when maximum temperature gain across the solar collector was recorded. As shown in Fig. 4, there was a substantial gain in air temperature at the solar collector outlet, which corresponded to a relative reduction in humidity. A significant decrease in air temperature across the drying chamber was recorded. As shown in Fig. 5, there was a slight increase in the relative humidity within the drying chamber due to the moisture evaporation during the drying process

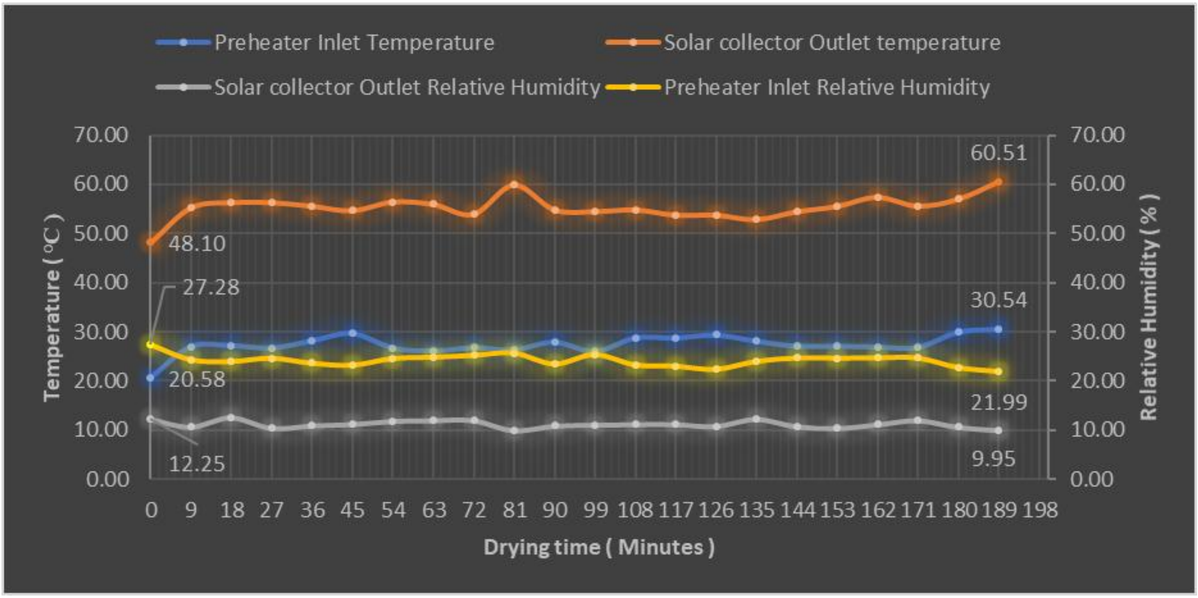

Fig. 4. Temperature and relative humidity variation across the preheater-to-solar collector unit

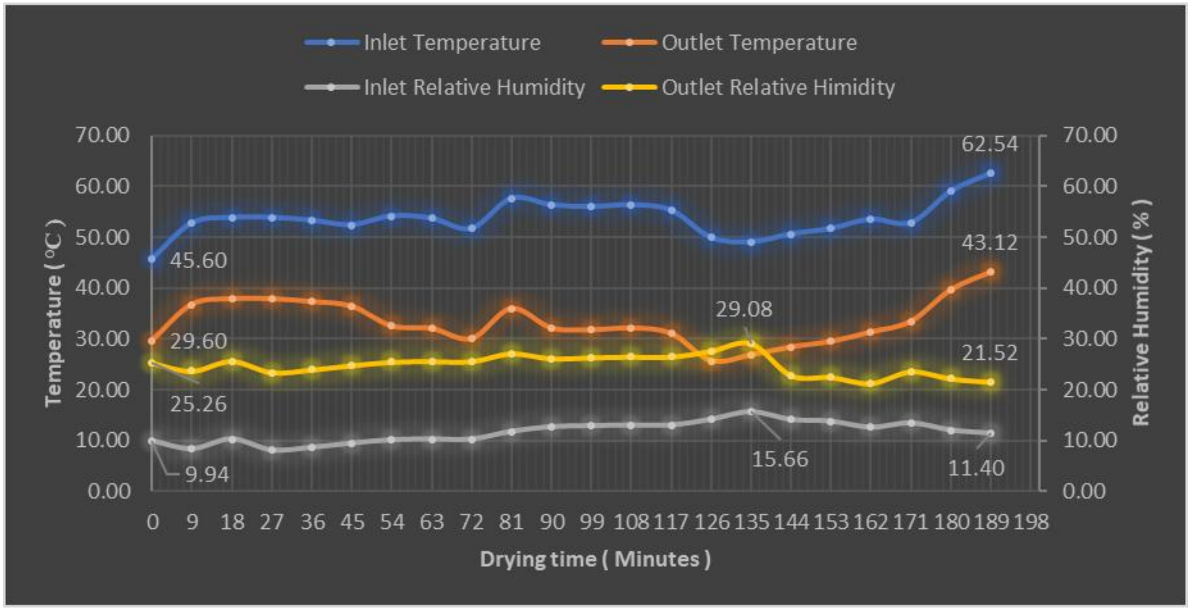

Fig 5. Temperature and relative humidity variation across the drying chamber unit.

2) *Average Temperature and Relative Humidity at 36 °C Preheated Air*

The graphs shown in Fig. 6 and Fig. 7 indicate the results during the first 3 hours and 9 minutes as measured by the sensors when air entering the solar collector was preheated to 36 °C.

It is also evident from the graphs that there was a gain in temperature during air heating (across the solar collector) and a reduction in air temperature during drying processes (across the drying chamber). However, the gain in air temperature was not consistent throughout the drying process.

Retrieval Number: 100.1/ijitee.B82831210220
DOI: 10.35940/ijitee.B8283.0210421
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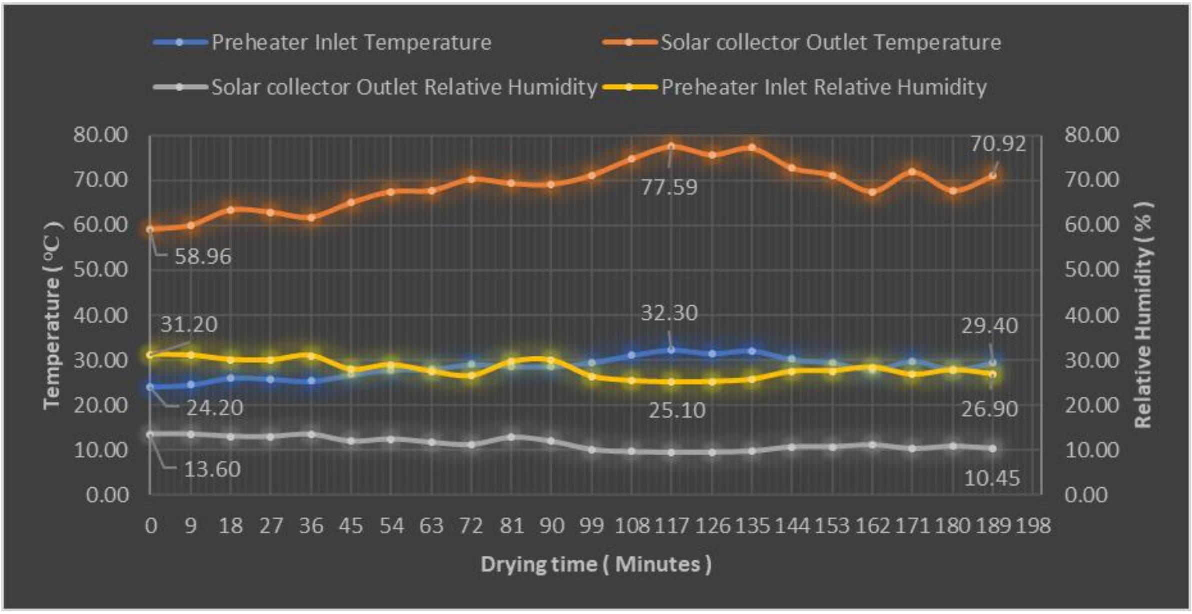

Fig. 6. Temperature and relative humidity variation across the preheater-to-solar collector unit

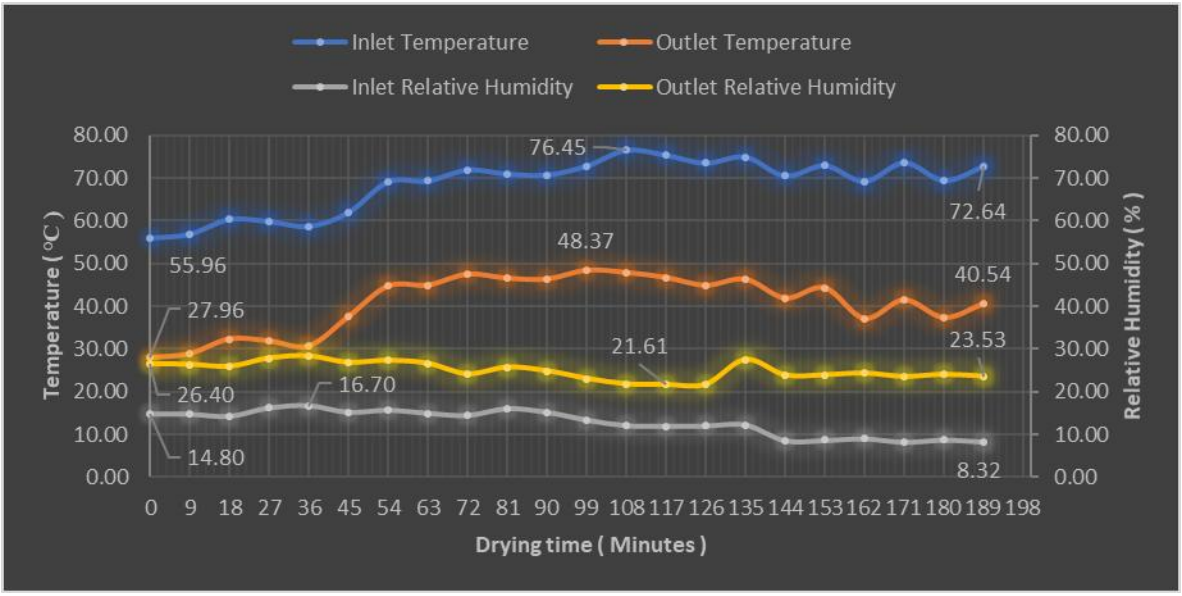

Fig. 7. Temperature and relative humidity variation across the drying chamber unit

3) *Average Temperature and Relative Humidity at 40 °C Preheated Air*

The experiment included preheating the air to 40 °C before entering the solar collector unit. The temperature and relative humidity across the solar dryer system obtained during the first 3 hours and 9 minutes are shown in Fig. 8 and Fig. 9. The results indicate these were the highest drying air temperature recorded during the experiment.

High temperatures associated with very low relative humidity at the solar collector's outlet yielded maximum drying parameters at the drying chamber. A comparison of results from Fig. 4 and Fig. 8 indicates that preheating air from 30 °C to 40°C results in a maximum temperature gain of about 18 °C. The ambient weather conditions vary with time, consequently, these inconsistencies result in the fluctuations of the drying parameters, as shown by the graphs in all the above figures. Although the preheating of air significantly improves the drying process, it is crucial to consider the optimum temperature for drying specific food items. Depending on the application, different food items such as grains have various temperatures recommended for safe drying.

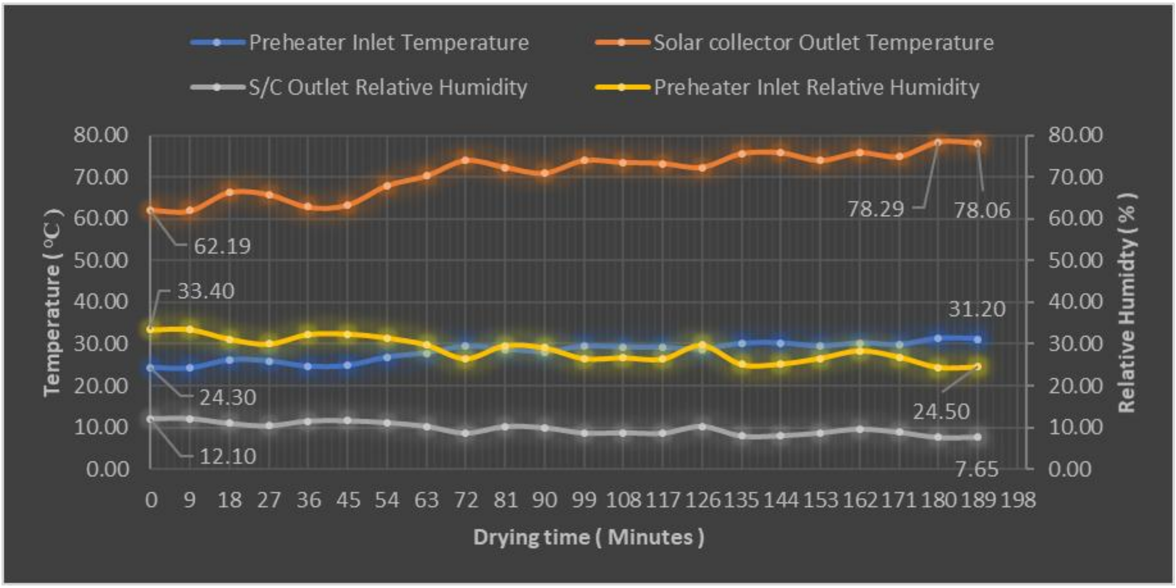

Fig. 8. Temperature and relative humidity variation across the preheater-to-solar collector unit

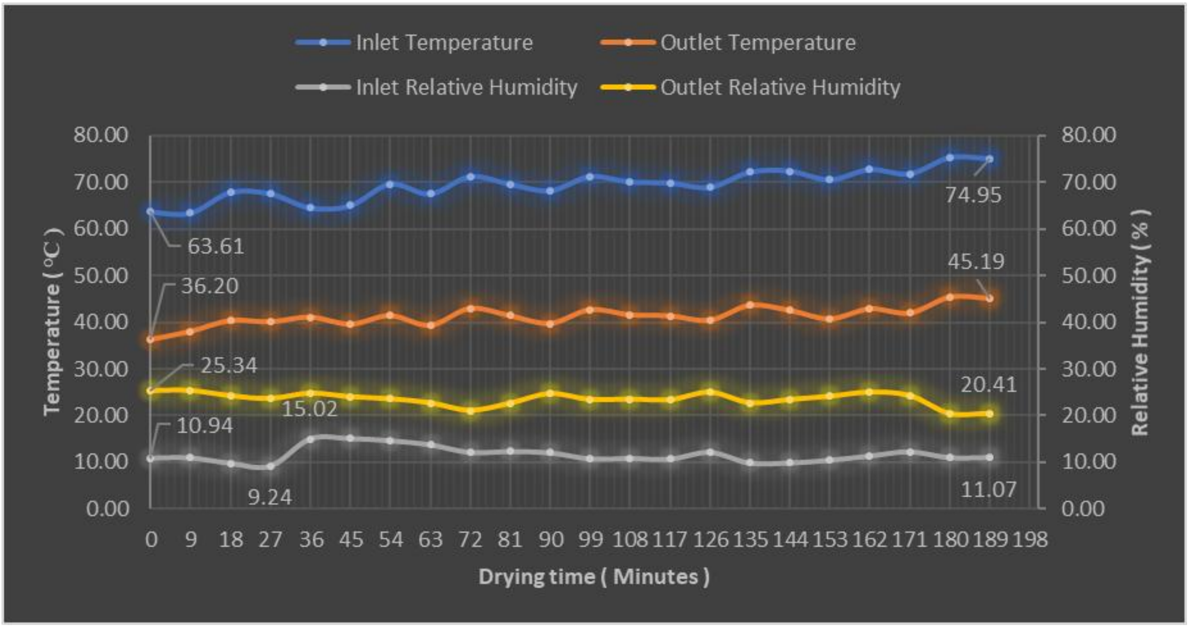

Fig. 9. Temperature and relative humidity variation across the drying chamber unit

C. Variation of Moisture Content During Drying Processes

The moisture content results measured using a moisture meter during the experimental period are shown in the figures below. Fig. 10 shows the results of day 1 to day 3, Fig. 11 shows the results of day 4 to day 6, and Fig. 12 shows the results of the last three days (day 7-9). Fig. 13 shows the results of moisture content during open sun drying that were recorded between day 1 and day 3. The final moisture content and the corresponding drying time are displayed at the end of each line graph. For example, in Fig. 10 air that was preheated to 30 ℃ with a flow speed of 0.5 m/s yielded a final moisture content of 12.8 % (wb) in 394 minutes (6 hours and 34 minutes)

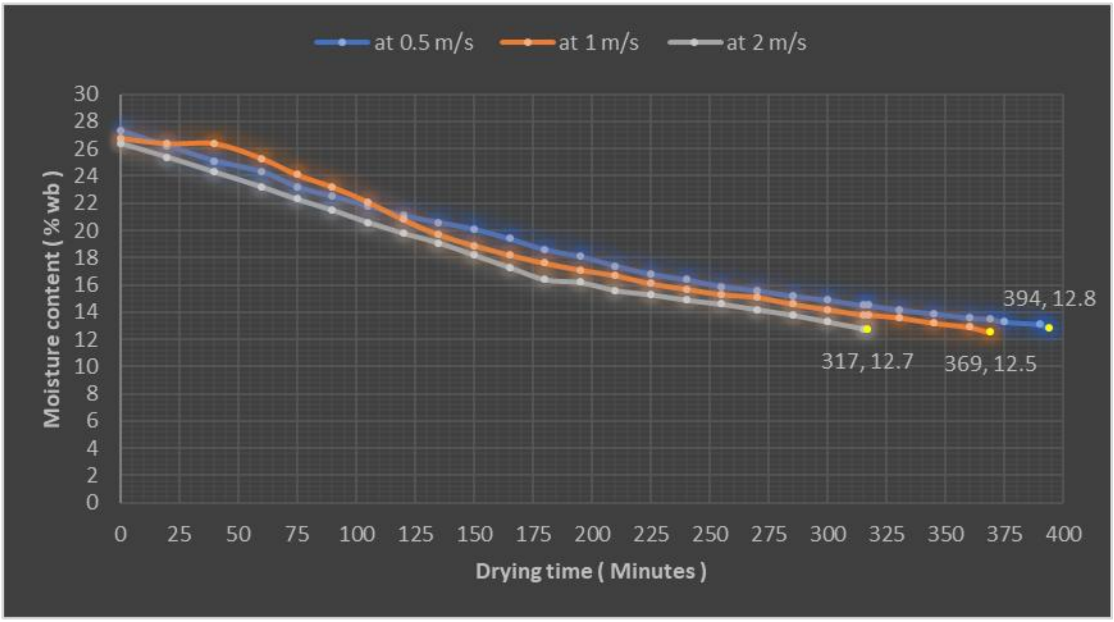

Fig. 10. Moisture content of maize corn at various air flow with 30 °C preheated air

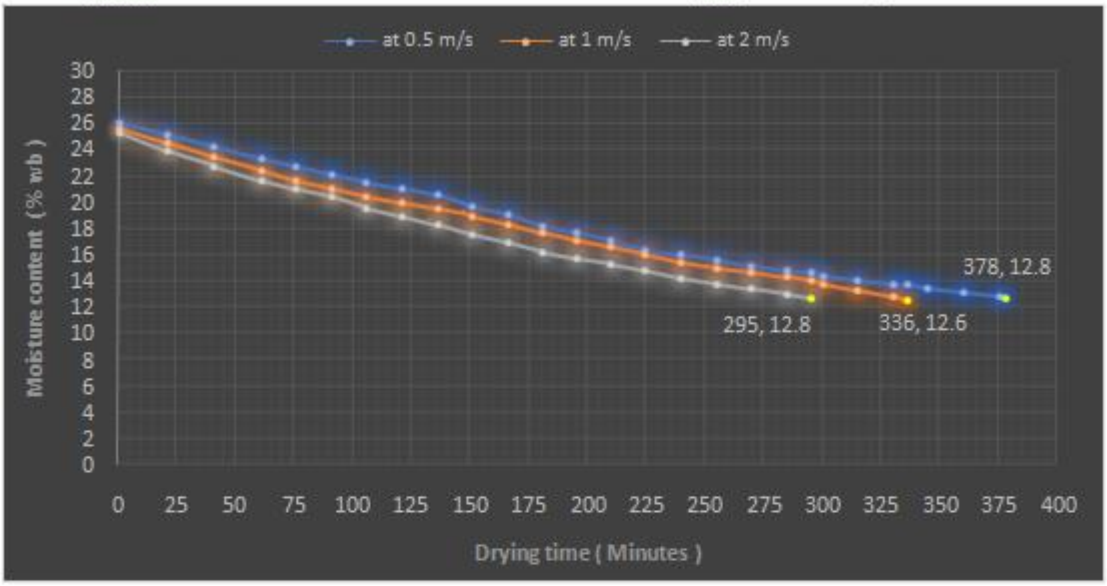

Fig. 11. Moisture content of maize cobs at various air flow with 36 °C preheated air

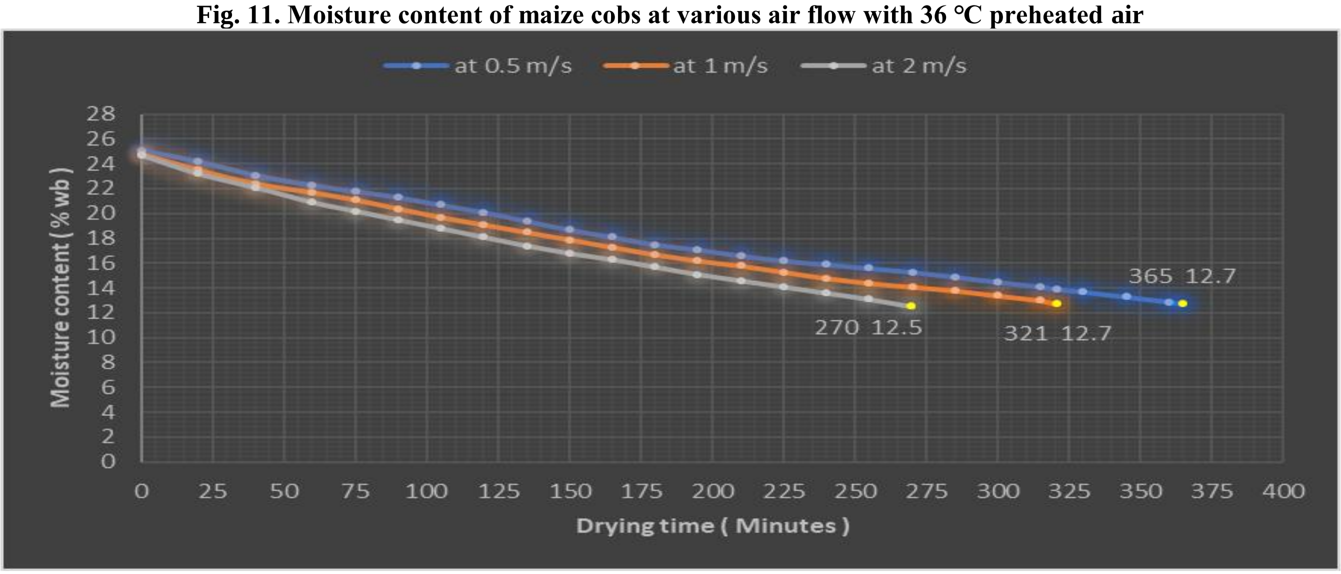

Fig. 12. Moisture content of maize cobs at various air flow with 40 °C preheated air

Retrieval Number: 100.1/ijitee.B82831210220
DOI: 10.35940/ijitee.B8283.0210421
Journal Website: www.ijitee.org

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication

International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-10 Issue-4, February 2021

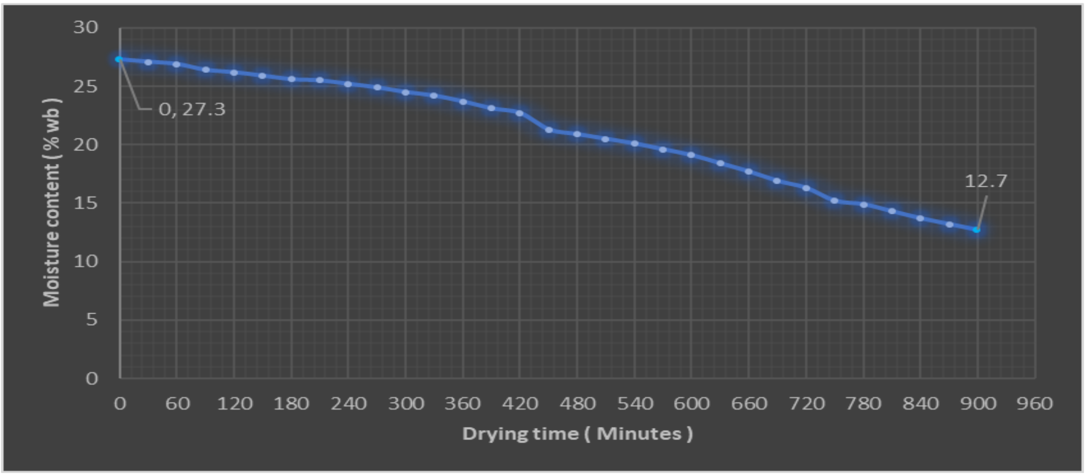

Fig. 13. Moisture content of maize cobs during open sun drying

Overall, the results shown in the above figures indicate that maximum drying was achieved at an airflow of 2 m/s using 40 °C preheated air. The average initial moisture content of the maize cobs was 24.7 % (wb), and this was reduced to a final moisture content of 12.5 % (wb) in 270 minutes (4 hours and 30 minutes) as shown in Fig. 12. The minimum drying of maize cobs using the solar dryer system occurred in 394 minutes (6 hours and 34 minutes) at an airflow of 0.5 m/s as shown in Fig. 10. Drying of maize cobs in the open sun was conducted in order to develop a reference of improvement. Open sun drying is associated with many disadvantages such as longer drying time. This can be seen in the results in Fig. 13 whereby drying of maize cobs was achieved in 900 minutes (15 hours). A drying period of 15 hours was achieved after two consecutive days of open sun drying experiment.

D. Performance Evaluation

This section analyzes the performance of the dryer system using the experimental results. The results enable the minimum and maximum thermal efficiencies of the dryer system to be calculated. In addition, minimum and maximum drying rates are also calculated to determine the hourly moisture removal from maize cobs.

1) *Dryer Efficiency*

The process of drying food products involves the removal of water that is contained within the food structure. In order for this process to happen, a minimum amount of heat is required to evaporate water from the food products. The minimum amount of heat required to evaporate water is referred to as the latent heat of vaporization. In practice, sensible heat needs to be incorporated in calculating the efficiency of the dryer. Sensible heat accounts for the heat required to raise the temperature of the food product being dried. In this study, the sensible heat was calculated based on the specific heat capacity of grains as defined by equation 4 provided in the study of Verma and Prasad [12].

In this study, the dryer system's efficiency was defined as the ratio of the latent heat of vaporization plus sensible heat to the useful heat gained by drying air as it navigates from the preheater through the solar collector to the drying chamber. Equation (3) indicates the formula used in calculating both maximum and minimum efficiency.

$$\eta_{sys} = \frac{(M_w \times L_v) + (M_g \times C_{pg} \times \Delta T)}{M_a\, C_{pa}(T_{dc} - T_{amb})} \quad (3)$$

Whereby:
M_w = Mass of evaporated water (kg)
L_v = Latent heat of vaporization (kJ/kg)
M_g = Mass of the dried product (kg)
ΔT = Change in temperature of maize grains (°C)
M_a = Total quantity air needed to evaporate water (kg)
T_{dc} = Temperature of drying air entering the drying chamber (°C)
T_{amb} = Temperature of ambient air (°C)
C_{pa} = Specific heat capacity of air (kJ/kg.K)
C_{pg} = Specific heat capacity of maize grains (kJ/kg.K)

$$= 1.3066 + 1.2045 M_d + 0.0198 T \quad (4)$$

Whereby "T" and "M_d" are the dried grains' temperature and moisture content, respectively.

The mass of evaporated water is calculated based on the percentage of moisture content and the food products' total mass before drying. This relationship is given by (5).

$$M_w = M_p \left(\frac{M_i - M_f}{100 - M_f}\right) \quad (5)$$

Whereby:
M_p = Total mass of the maize grains = 1.41 kg (6 maize cobs were used per solar drying experiment with an average mass of 235 g each)
M_i = Initial moisture content of maize grains (% wb)
M_f = Final moisture content of maize grains (% wb)

Maximum dryer system efficiency

The maximum efficiency calculations were based on the experimental results for maximum drying, which was achieved when air was preheated to 40 °C at an air flow of 2 m/s. At maximum efficiency, drying of maize cobs was achieved in 4 hours and 30 minutes, and the volume of air needed for drying was 14.076 m^3. Using information from Fig. 9 and Fig. 12, maximum efficiency can be calculated by substituting the following information.

M_i =24.7 %
M_f = 12.5 %
M_w = 0.197 kg
$M_g = M_p - M_w$ = 1.213 kg
M_a = $density \times volume$ = 16.666 kg (using air density of 1.184 kg at room temperature)

C_{pg} = 1.952 kj/kg.k (using final moisture content and assuming maize are at room temperature of 25 °C after drying)
ΔT = 20.19 °C
T_{amb} = 25 °C (assumed to be at room temperature)
T_{dc} = 74.95 °C
L_v = 2257 kj/kg
C_{pa} = 1.006 kj/kg.k
The above information yielded a maximum efficiency, η_{sys} = **58.8 %**

Minimum dryer system efficiency

The minimum efficiency calculations were based on the experimental results for minimum drying, which was achieved when air was preheated to 30 °C at an airflow of 0.5 m/s. At minimum efficiency, drying of maize cobs was completed in 6 hours and 34 minutes, and the volume of air needed for drying was 26.721 m^3. Using information from Fig. 5 and Fig. 10, minimum efficiency can be calculated by substituting the following information:
M_i =27.3 %
M_f = 12.8 %
M_w = 0.234 kg
$M_g = M_p - M_w$ = 1.176 kg
$M_a = density \times volume$ = 31.638 kg (using air density of 1.184 kg at room temperature)
C_{pg} = 1.956 kj/kg.k (using final moisture content and assuming maize are at room temperature of 25 °C after drying)
ΔT = 18.12 °C
T_{amb} = 25 °C (assumed to be at room temperature)
T_{dc} = 62.54 °C
L_v = 2257 kj/kg
C_{pa} = 1.006 kj/kg.k
The above information yielded a minimum efficiency, η_{sys} = **47.7** %

2) *Drying Rate*

The drying rate of a solar dryer is defined as the ratio of the mass of evaporated water 'M_w' from the food product to the time 't_d' required to dry the food product. This relationship can be expressed by (5) as follows:

$$Drying\ rate\ (kg/hr) = \frac{M_w}{t_d} \quad (5)$$

Using the information provided in the previous section, the following can be derived:
Maximum drying rate = **0.0438** kg/hr
Minimum drying rate = **0.0356** kg/hr

The solar dryer system's efficiency at minimum drying condition (47.7 %) is even higher than the initial efficiency (36 %) of the solar dryer system before modification. This is a clear indication that operating a solar dryer in mixed-mode operation with a preheater/backup-up heater and forced convection improves the dryer's performance. An efficient solar dryer will yield high drying capacity, resulting in enhanced grains harvest and storage capacity.

V. CONCLUSION

The performance of a forced convection mixed-mode solar grain dryer integrated with a preheater was evaluated in this study. The dryer system's performance results indicated a maximum thermal efficiency of 58.8 % with a corresponding drying rate of 0.0438 kg/hr. The minimum thermal efficiency for the dryer system was 47.7 %, with a corresponding drying rate of 0.0356 kg/hr. The fastest drying time of maize cobs was achieved in 4 hours and 34 minutes (within one day of drying) using the dryer system from an initial moisture content of 24.7 % wb to 12.5 % wb. Open sun drying yielded the slowest drying time of 15 hours (within 3 days of drying) from an initial moisture content of 27.3 % wb to 12.7 % wb. The results show a significant improvement of the mixed mode dryer system compared to the initial thermal efficiency of the indirect solar dryer before modification which was 36 %. This is a clear indication that operating a dryer system in mixed mode operation using forced convection drying air with the assistance of a preheater or backup heater can significantly improve drying processes. An efficient dryer system can lead to improved harvests and increased grain storage capacity.

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