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# Design and Evaluation of Solar Grain Dryer with a Back-up Heater

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**Abstract:** The aim of the study was to design and construct a solar grain dryer integrated with a simple biomass burner using locally available materials. This was to address the limitations of the natural sun drying for example drying exposure, liability to pests and rodents, over-dependence on sun and escalated cost of mechanical dryers. This became beneficial especially in reducing post-harvest losses as well as helping in the preservation of agricultural product. The dryer is composed of solar collector, drying chamber, back-up heater and airflow system. The design was based on the study area of Mau summit located in Nakuru County, Kenya. The average ambient conditions were 26°C air temperature and 72% relative humidity with daily global solar radiation incident on horizontal surface of about 21.6 MJ/m$^2$/day. A minimum of 3.77 m$^2$ solar collector area was required to dry a batch of 100 kg maize grain in 6 h with natural convection from the initial moisture content of 21% to final moisture content of 13% wet basis. A prototype dryer designed was fabricated with minimum collector area of 0.6 m$^2$ and used in the experiment. Forced convection was employed to reduce drying time. The thermal efficiencies of the solar and solar assisted dryer were 39.9 and 57.7%, respectively. The back-up heating system improved the efficiency of the dryer by 17.8% and reduced drying time substantially.

**Keywords:** Back-up heater, design, grain, solar collector, solar drying

## INTRODUCTION

In Kenya, drying of agricultural produce is accomplished majorly through open-air drying/Sun-drying and mechanized dryers, with limited application of solar dryers. Open-air drying is the oldest, most inexpensive and extensively used option since early times, practice in most of the regions in many parts of the world including Kenya's rural areas, but it is associated with various limitations which includes; dependence on weather conditions, labor intensive, unhygienic, unreliable, time consuming, non-uniform drying and requires a large area for spreading the produce out to dry and in some places have failed to produce expected results.

Mechanized dryers though faster and gives a better quality product, they are expensive and requires substantial quantities of fuel or electricity to operate, leading to high cost of drying (Ajay *et al*., 2009).

Maize being the most important staple food in sub-Saharan Africa has over time been preserved through this method. According to Kenya Maize Development Programme (KMDP) maize is the primary staple food crop in the Kenyan diet with an annual per capita consumption rate of 98 kg-contributing about 35%-of the daily dietary energy consumption.

Indeed, 90% of the rural households grow maize and production is dominated by small scale farmers who produce 75% of the overall production. The other 25% is grown by large scale farmers (Erastus, 2011).

A significant percentage of post-harvest losses and aflatoxins contamination are related to improper and/or untimely drying of foodstuffs such as cereal grains, pulses, tubers, meat and fish among others (Togrul and Pehlivan, 2004). Therefore, the intermediate drying technology that takes care of sun-drying disadvantages, ecofriendly and economically feasible to small scale farmers is the application of solar dryers which comprises of collector, a drying chamber and sometimes a chimney.

One significant limitation of solar dryer is that it can only be used during the daytime when there is adequate solar radiation. This will limit production and moreover it can result in an inferior product. For commercial producers, the ability to process continuously with reliability is important to satisfy their markets. Therefore, it is necessary to provide solar dryer with any form of back-up heating.

**Objectives:** Objectives of this study were:

- To design and fabricate collector to harness solar thermal energy.
- To design and fabricate solar dryer pertinent parts which include drying chamber, back-up heater and

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airflow system as well as assemble them to a complete prototype system.
- To test and evaluate the thermal performance characteristics of the designed prototype dryer.

## MATERIALS AND METHODS

**Solar dryer design consideration:** The following points are considered generally in design of direct natural/forced convection solar dryer system:

- The amount of moisture to be removed from a given quantity of maize grain
- Harvesting period during which the drying is needed
- The daily sunshine hours for the selection of the total drying time
- The quantity of air needed for drying
- Daily solar radiation to determine energy received by the dryer per day
- Wind speed for the calculation of air vent dimensions

**Design procedure and calculations:** The size of the dryer was determined as a function of the drying area needed per kilogram of maize grain. The drying temperature was established as a function of the maximum limit of temperature the grain might support. From the climatic data of study area the mean average day temperature for September to December is 26°C and relative humidity is 72%. Hence, from the psychometric chart the humidity ratio is 0.015 $kg_{wv}/kg_{da}$. The maximum allowable drying temperature of maize grain without compromising its quality was maintained at 50°C and final moisture content of maize grain for safe storage as 13% wet basis.

To carry out design calculations and size of the dryer, the design conditions applicable to mau-summit were considered. Information regarding the type of crop to be dried, loading densities acceptable, the crop characteristics and the quantity per batch were needed with data concerning the geographical location of the dryer and climatic conditions during the harvest period. Overly, the conditions, assumptions and relationships summarized in Table 1 were used to calculate the design parameters of the solar maize grain dryer.

**Additional fundamental design constraints:** Forson *et al*. (2007), proposed additional design constraints applicable to naturals/forced convection based on previous research work to further assist in validating these dryer systems, some of which includes:

- The collector tilt (β) for maximum collection of incident solar radiation for all year round operation of a collector is to be taken as the latitude of the site where it is located in practice.
- The maximum height of the hot air column, H, is recommended to be between 2 and 6 m for corresponding total pressure across the dryer between 0.8 and 2.5 Pa.
- Simulation studies conducted in previous research showed that as the ratio of drying chamber area to the collector surface area is increased the overall drying efficiency increases. However, it was observed that for the ratio in the range of 1-2, there was no observable difference in the performance of the dryer. A value of 1.0 is therefore recommended as the ratio of the drying floor area to the collector surface area.
- The length-to-width ratio of solar collector (L/W) for optimum performance is in the range 1-2.

**Design calculations:**

**Total solar collector area:** From the total useful heat energy required to evaporate moisture and the

Table 1: Design specification and assumption

| Items | Condition and assumption |
|---|---|
| Location | Mau-summit (latitude 0.18°S and longitude 35.62°E) |
| Crop | Maize grain |
| Crop porosity, ξ | 0.42 |
| Bulk density, $\rho_{gr}$ (kg/m$^3$) | 721 |
| Loading bed void fraction, $\varepsilon_v$ | 0.70 |
| Drying period | September to December |
| Drying per batch; loading rate, $m_g$ (kg/batch) | 100 |
| Initial moisture content, $M_i$ (%) w.b | 21 |
| Final moisture content, $M_f$ (%) w.b | 13 |
| Ambient air temperature, $t_{am}$ (°C) | 26.00 (average for period; 2006-2010) |
| Ambient relative humidity, $RH_{am}$ (-) | 0.72 |
| Maximum allowable temperature, $t_{max}$ (°C) | 50 |
| Drying time (sunshine hours) $t_d$ (h) | 6 |
| Incident solar radiation, $I_h$ (MJ/m$^2$/day) | 21.60 (average for period; 2006-2010) |
| Wind speed, $w_s$ (m/s) | 2.20 |
| Collector efficiency, $\eta_c$ (%) | 50 |
| Average thickness of grain, $th_m$ (mm) | 9.13 |
| Vertical distance between two adjacent trays, *d* (cm) | 15 |
| Collector tilt angle, (°) | 0° |

Measurements and assumptions

net radiation received by the collector, the solar drying system collector area $A_c$, in $m^2$ can be calculated from the following equation:

$$A_c I\eta = E = m_a (h_f - h_i)\, t_d \tag{1}$$

Therefore, area of the solar collector is:

$$A_c = \frac{E}{I\eta} \tag{2}$$

where,

E = The total useful energy received by the drying air, kJ
I = The total global radiation on the horizontal surface during the drying period, in kJ/$m^2$
$\eta_c$ = The collector efficiency, which is assumed to be in the range of 30 to 50% (Sodha *et al*., 1987)

The collector area calculated from Eq. (2) yields $A_c = 3.77\ m^2$

**Design and fabrication of solar dryer pertinent parts:** The major parts of the solar dryer include: Drying chamber, back up heater, airflow system (ducts and fan system).

**Design calculations:**

**The amount of moisture to be removed from the product:** $m_w$ (kg) was calculated using the following equation:

$$m_w = m_p \frac{(M_i - M_f)}{(100 - M_f)} \tag{3}$$

where,

$m_p$ (kg) = The initial mass of product to be dried (100 kg)
$M_i$ (%), $M_f$ (%)= Wet basis are the initial moisture content and the final moisture content, respectively

According to Eq. (3), the mass of moisture evaporated is 9.2 kg.

**Final relative humidity or equilibrium relative humidity:** ERH (%), was calculated using sorption isotherms equation given as follows:

$$a_w = 1 - exp[-exp(0.914 + 0.5639 lnM)] \tag{4}$$

$$m_w = \frac{M_f}{(100 - M_f)} \tag{5}$$

$$ERH = 100 a_w \tag{6}$$

where,

$a_w$ = The water activity; M ($kg_w/kg_s$) dry basis

**The quantity of air needed for drying:** Using a psychometric chart and taking input air temperature of 26°C (dry bulb) and a relative humidity of 72%, the psychometric chart gives a humidity ratio of 0.015 kg water/kg dry air. When the solar collector heats air to optimum drying temperature of 50°C (dry bulb), the humidity ratio remains constant. If on passing through the grain, the air absorbs moisture until its relative humidity is equal to ERH (calculated), 57%. The psychometric chart shows the humidity ratio to be 0.021 kg water/kg dry air. The change in humidity ratio is therefore: 0.021-0.015 = 0.006 and the corresponding dry bulb temperature is 35.5°C.

From the gas laws Eq. (7):

$$PV = M_A RT \tag{7}$$

where,

P = The atmospheric pressure = 101.3 KPa
V = The volume of air in $m^3$
$M_A$ = The mass of the air in kg
T = The absolute temperature in Kelvin
R = The gas constant = 0.291 kPa $m^3$/kg K

For a humidity ratio increase of 0.006 kg water/kg dry air, each kg of water will require 1/0.006 = 166.67 kg dry air. For this calculation, the absolute temperature is 35.5+273 = 308.5 K and the volume of air needed to remove 1 kg of water is 147.71 $m^3$. Hence 9.2 kg will require 1358.89 $m^3$ volume of air to effect drying:

- The volume flow rate of air $V_a$ ($m^3$/h) is calculated as shown below:

$$V_a = \frac{W_a}{t_d} \tag{8}$$

$W_a$ = Quantity of air required in $m^3$ = 1358.89 $m^3$
$t_d$ = Total drying time = 6 h (a batch daily)
$V_a$ = 1358.89/6 = 226.48 $m^3$/h (0.06 $m^3$/s)

- Mass flow rate of air, $m_a$, kg/h was calculated as below:

$$m_a = \rho_a \times V_a \tag{9}$$

$\rho_a$ = Density of drying air (kg/$m^3$) = 1.2 kg/$m^3$
$V_a$ = Volumetric air flow rate

This calculation yields 271.78 kg/h, (0.08 kg/s).

**The quantity of heat required to evaporate the $H_2O$ would be:**

$$E = m_a (h_f - h_i)\, t_d \tag{10}$$

where,
E = Total heat energy, kJ
$m_a$ = Mass flow rate of air, kg/h
$h_f$ and $h_i$ = Final and initial enthalpy of drying and ambient air, respectively, $kJ/kg_{da}$ read using psychometric charts
$t_d$ = Drying time, h

**Average drying rate:** Average drying rate, $m_{dr}$, was determined from the mass of moisture to be removed by solar heater and drying time by the following equation:

$$m_{dr} = \frac{m_w}{t_d} \tag{11}$$

**Sizing of the dryer chamber:** The breadth of the drying chamber, B, is made equal to the Width (W) of the air-heater.

Thus, the length of the drying chamber, $L_{dc}$, is determined from the relation:

$$L_{dc} = \frac{A_{dc}}{W} \tag{12}$$

**Air vent dimensions:** The air vent was calculated by dividing the volumetric airflow rate by wind speed:

$$A_v = \frac{V_a}{V_w} \tag{13}$$

where,
$A_v$ = The area of the air vent, $m^2$
$V_w$ = Wind speed, m/s

The length of air vent, $L_v$ will be equal to the length of the dryer. The width of the air vent can be given by:

$$B_v = \frac{A_v}{L_v} \tag{14}$$

where,
$B_v$ = The width of air vent, m

**Pressure drop through the drying bed:** The resistance to the flow of air through a packed bed of agricultural produce is expressed in the form (Jindal and Gunasekaran, 1982; Forson *et al*., 2007):

$$u = a\,(\Delta \frac{P_B}{h_L}) \tag{15}$$

where,
$u$ = The superficial air velocity
$h_L$ = The drying bed thickness
$a$ = A constant whose value is determined experimentally

For natural circulation of air through a thin layer of crop ($h_L \leq 0.20$ m), the value of the constant is 0.465 $m^3$s/kg.

The air velocity (u) can be assumed as the maximum velocity at the exit of the solar collector and equal to 0.4 m/s (Forson *et al*., 2007). The pressure drop across the crop bed ($\Delta P_B$) is calculated using the optimum drying bed thickness of 0.2 m and for our design it was found to be 0.17 Pa. The total pressure drop across the solar collector and the air vent is comparable to that across the drying bed and hence the total pressure drop of the system is approximately twice the pressure drop of the drying bed. Hence, ($\Delta P_T = 2$ ($\Delta P_B$). When all pressure drops are accounted for, experience has shown that, the gross pressure drop is about six times the value of $\Delta P_T$ (Forson *et al*., 2007) and given by relation:

$$\Delta P_T = 6 \text{ x } (2\Delta P_B) \tag{16}$$

**Height of the hot air column:** The height of the hot air column is the minimum height of the exit vents above the collector inlet for moist air escape to the ambient under air circulation by natural convection. In arriving at the height of the air column, it is assumed that the dryer functions under steady state conditions. It is further assumed that:

- The depth of the drying bed, $h_L$, is small compared to height, H, of the hot air column
- The whole structure is air tight and ambient air enters through the inlet and the moist warm air escapes through the exit vent (s)
- The steady state average values of the temperature and density of the hot air inside the dryer are $T_{dryer}$ and ρ*, respectively

Applying Bernoulli's equation between the relevant sections of the dryer and simplifying the resulting expressions leads to the relation:

$$H = \frac{\Delta P_T}{g(\rho_a - \rho^*)} = \frac{\Delta P_T R}{g(\frac{1}{T_{amb}} - \frac{1}{T_{dryer}})P_a} \tag{17}$$

where, $\Delta P_T$ is the total pressure drop through the dryer. With the value $\Delta P_T$ = 6 x 0.34 Pa, the height of the hot air column above the air inlet H was found to be 2.4 m. In the construction of the dryer, an allowance is made for the height of the solar collector inlet above the ground level. The height of the solar collector inlet vent above the ground level, y, should be at least 0.40 m to allow air to flow naturally through it.

**Specified and computed design parameters:** Table 2 shows the computed results of the pertinent design parameters of the design. The prototype of the design

Table 2: Pertinent design parameters

| Parameter | Units | Data or equation used | Value | Source |
|---|---|---|---|---|
| Initial humidity ratio, $\omega_i$ | $kg_{wv}/kg_{da}$ | $t_{am}$, $RH_{am}$ | 0.015 | Psychometric chart |
| Initial enthalpy, $h_i$ | $kJ/kg_{da}$ | $t_{am}$, $RH_{am}$ | 65.000 | Psychometric chart |
| Equilibrium relative humidity, $RH_f$ | % | $M_f$ and isotherms Eq. (6) | 57.000 | |
| Final enthalpy, $h_f$ | $kJ/kg_{da}$ | $\omega_i$, $t_f$ | 90.000 | Psychometric chart |
| Final humidity ratio, $\omega_f$ | $kg_{wv}/kg_{da}$ | $RH_f$, $h_f$ | 0.021 | Psychometric chart |
| Mass of water to be evaporated, $m_w$ | kg | Eq. (3) | 9.200 | |
| Average drying rate, $d_r$ | $kg_{wv}/h$ | Eq. (11) | 1.530 | |
| Air flow rate, $m_a$ | kg/h | Eq. (9) | 271.780 | |
| Volumetric airflow rate, Va | $m^3/h$ | Eq. (8) | 226.480 | |
| Total useful energy, E | MJ | Eq. (10) | 40.770 | |
| Solar collector area, $A_c$ | $m^2$ | Eq. (2) | 3.770 | |
| Vent area, $A_v$ | $m^2$ | Eq. (13) | 0.030 | |
| Air pressure drop, P | Pa | Eq. (16) | 2.040 | Entire system |
| Vent length, $L_v$ | m | Spec. | 1.260 | |
| Vent width, $B_v$ | m | Eq. (14) | 0.020 | |

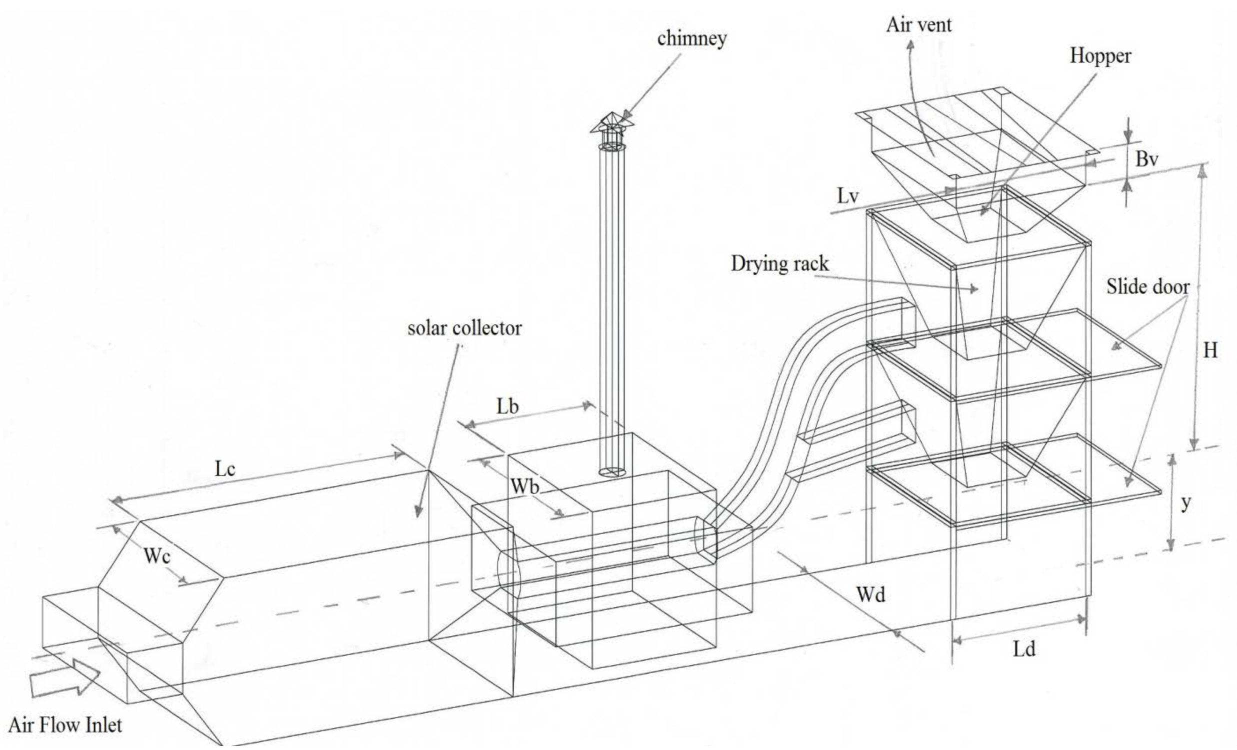


Fig. 1: Schematic view of the solar dryer with back up heater

Table 3: Prototype pertinent parts dimensions

| Parameter | Units | Prototype |
|---|---|---|
| Solar collector | | |
| Length, $L_c$ | m | 1.00 |
| Width, $W_c$ | m | 0.60 |
| Collector area, $A_c$ | $m^2$ | 0.60 |
| Solar dryer | | |
| Length, $L_d$ | m | 0.50 |
| Width, $B_d$ | m | 0.60 |
| Air vent | | |
| Length, $L_v$ | m | 0.50 |
| Width, $B_v$ | m | 0.01 |
| Back up heater | | |
| Length, $L_b$ | m | 0.70 |
| Width, $W_b$ | m | 0.60 |
| Depth, $D_b$ | m | 0.60 |
| Height of air column, H | m | 0.96 |
| Height of collector inlet above ground level, y | m | 0.40 |

with a minimum solar collector area of 0.6 $m^2$ was fabricated and used in experimental drying tests.

**Construction of prototype dryer:** The main parts of the dryer so fabricated are solar collector system, biomass burner and drying chambers. The critical dimensions are summarized in Table 3 and illustrated in the schematic view of the solar dryer Fig. 1.

## RESULTS AND DISCUSSION

The experiment results were obtained from an experiment carried out in three consecutive months. The results include that of the solar drier, biomass heater alone and then the combination of the two.

The ambient temperatures also varied greatly with solar radiations. The average ambient temperatures from 11.00 am to 4.00 pm range was 26.8 to 28.0°C on the months of August, September and October (Fig. 2).

As shown from the above graph, the solar irradiation and ambient temperatures were at maximum during noon (1200-1300 h), then decreases gradually at sun set.

**Open sun drying:** During the performance of the dryer tests, sun drying was also performed by spreading the same amount of maize grain sample in the sun on the open. The result of the experiments was tabulated and the performance of the method analyzed using the drying rate. The maize moisture content decreased with change in time from 19.3 to 13.2% within 6 days of 4 h drying daily.

Given that; Mass of moisture removed, $M_w$ (0.25 kg) over drying period of, $t_d$ (24 h). Then the average drying rate obtained is 0.0104 kg/h

**Solar collector performance:**

**No load:** The temperatures of the system were measured when the solar dryer was operated with no load in it. The inlet and outlet temperatures were measured for 3 h before loading the dryer with maize samples.

The Fig. 3 shows the relationship between temperatures ($T_{in}$ and $T_{out}$) of the system within solar collector chamber. The solar heater increases the air temperatures greatly and the outlet air temperatures are higher than the inlet temperatures by an average value of 4°C.

Therefore, the steady state efficiency of the solar air collector using Hottel-Whillier-Bliss equation (Forson *et al*., 2007), given as:

$$\eta_c = \frac{Q_g}{I_T A_c}$$

where,

$Q_g$ = Mass flow rate (0.12 kg/s) ×specific heat capacity of dry air (1.006 KJ/kg.K) ×Average change in temperature (2.78 K)

$A_c$ = Area of the collector (0.6 $m^2$)

$I_T$ = Average solar insolations (0.958 KJ/s), the thermal efficiency of the collector $\eta_c$ was found to be 59%

**Loaded solar drier:** The solar drier was loaded with maize grains during active solar radiations, which was from 11 am until 3 pm for three consecutive days in each month. The maize moisture content decreased with change in time from 19.3 to 13.2% within 3 days of 4 h drying daily.

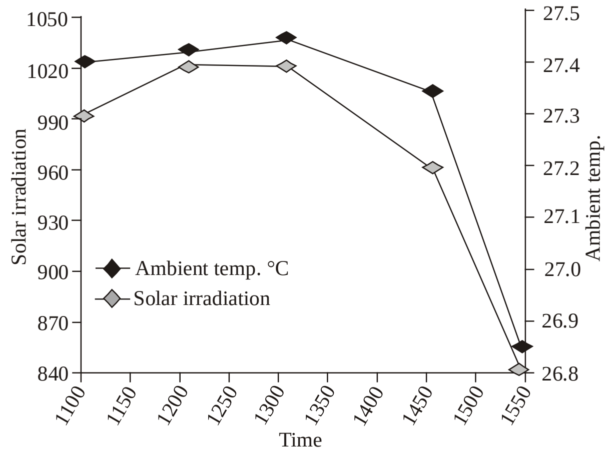


Fig. 2: Variation of ambient temperatures (°C) and solar irradiance (W/$M^2$) with time (h)

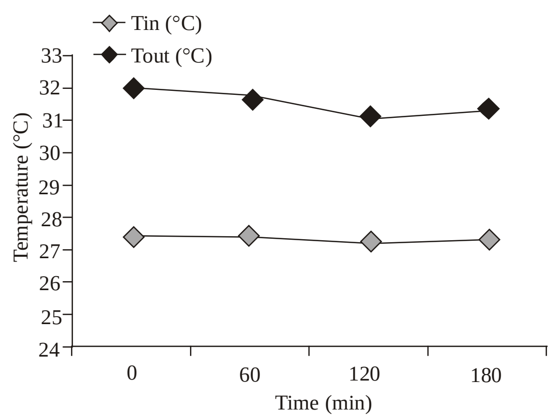


Fig. 3: Temperatures at solar collector chamber

**Solar drier assisted by biomass heater:** The experiment was performed by combining the solar heater and biomass heater to dry the maize sample. The experimental results were tabulated and the performance of the system was analyzed using the drying rate as shown in the Table 4 and Fig. 4.

The maize moisture content decreased exponentially with change in time from 19.3 to 13.7% within 3 h.

**Thermal efficiencies:**

**Solar dryer (solar collector as the only source of heat):** When solar energy was the only heat source for drying, system efficiency can be defined as the ratio of thermal equivalent of the evaporated water plus the quantity of heat used to raise the temperature of the product to the useful heat gained by drying air from the solar collector. Where, $Q_a$ is the useful heat gained by the dry air (Tarigan and Tekasakul, 2005). Hence:

$$\eta_{syst} = \frac{(M_W \times L_v) + (M_g \times Cp_g \times \Delta T)}{Q_a}$$

Table 4: Solar assisted dryer experiment results

| Time (min.) | Solar chamber $T_{in}$°C | Solar chamber $T_{out}$ °C | Solar chamber ΔT°C | Heater chamber $T_{in}$°C | Heater chamber $T_{out}$°C | Heater chamber ΔT°C | Drying chamber $T_{out}$°C | Drying chamber Wt. of maize, kg | Drying chamber MC (% ) |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 27.4 | 31.7 | 4.3 | 31.7 | 43.6 | 11.9 | 36.4 | 4.10 | 19.3 |
| 10 | 27.7 | 30.7 | 3.0 | 30.7 | 46.8 | 16.1 | 34.8 | | |
| 20 | 27.4 | 31.1 | 3.7 | 31.1 | 46.7 | 15.6 | 35.3 | | |
| 30 | 27.4 | 31.3 | 3.9 | 31.3 | 46.5 | 15.2 | 36.3 | | 16.3 |
| 40 | 27.4 | 32.7 | 5.3 | 32.7 | 48.0 | 15.3 | 40.0 | | |
| 50 | 27.4 | 33.0 | 5.6 | 33.0 | 48.0 | 15.0 | 42.3 | | |
| 60 | 27.4 | 31.2 | 3.8 | 31.2 | 48.5 | 17.3 | 45.3 | | 14.8 |
| 70 | 27.2 | 31.4 | 4.2 | 31.4 | 49.7 | 18.3 | 46.0 | | |
| 80 | 28.1 | 29.3 | 1.2 | 29.3 | 46.9 | 17.6 | 45.4 | | 14.2 |
| 100 | 27.1 | 29.0 | 1.9 | 29.0 | 44.2 | 15.2 | 43.5 | | |
| 120 | 27.1 | 29.2 | 2.1 | 29.2 | 44.9 | 15.7 | 44.2 | | 13.9 |
| 140 | 27.0 | 28.0 | 1.0 | 28.0 | 44.8 | 16.8 | 44.6 | | 13.8 |
| 160 | 26.8 | 27.8 | 1.0 | 27.8 | 44.7 | 16.9 | 44.7 | | |
| 180 | 26.9 | 27.9 | 1.0 | 27.9 | 44.8 | 16.9 | 44.7 | 3.87 | 13.7 |

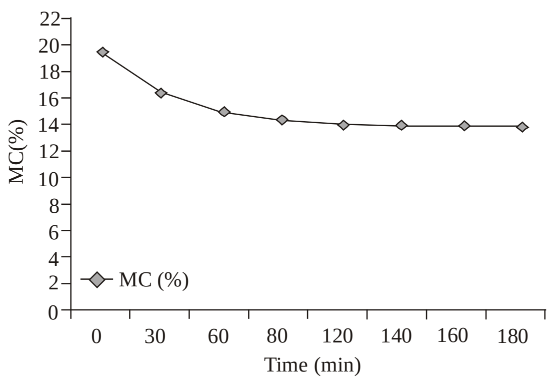


Fig. 4: Drying curve in the solar assisted drying mode

where, $Q_a = M_a C_{pa}$ ($T_{\text{into drying chamber}}$ - $T_{\text{ambient temperature}}$), ($M_a$ = 0.27 kg/s; $Cp_a$ = 1.006 KJ/kg.k, $T_{in}$-$T_{amb}$ = 3.7K); $M_w$ = mass of evaporated water (0.27 kg), $L_V$ = latent heat of vaporization (2270 KJ/Kg), Mg = mass of the grains dried (4.1 kg), $C_{pg}$ = specific heat capacity of the grains (1676.58 KJ/Kg.k) and ΔT = change in temperature (2.43 K). Therefore the system efficiency in this set up when the solar collector is the only heat source was found to be 39.9%.

**Biomass heater:** The overall thermal efficiency of the heater can be defined as the ratio of useful heat transferred to the drying air to the energy potential of fuel (Bena and Fuller, 2002). This efficiency is a product of the combustion efficiency and the efficiency of heat transfer to the air. In this project an overall efficiency of the heater, was calculated as:

$$\eta_{over} = \frac{heat\ transfered\ \ to\ air\ entering\ \ the\ drying\ \ chamber}{calorific\ \ value\ \ of\ biomass\ \ used}$$

Using temperature data recorded 4 h 40 min of back-up heating operation, with approximately 10 kg wood-fuel used with calorific value as 13.1 MJ/kg, where heat transferred to the air given as $M_a C_{pa}\ (T_{out} - T_{in})$ where Ma = 0.27 kg/s, $C_{pa}$ = 1.006 kJ/kgK and ($T_{out}$-$T_{in}$) = 15.5 K, an overall efficiency of the back-up heater was found to be 54%.

**Solar dryer with back-up heater as additional source of heat:** The overall thermal efficiency of the assisted solar dryer can be defined as the ratio of thermal equivalent of the evaporated water plus the quantity of heat used to raise the temperature of the product to the useful heat gained by drying air from both solar collector and the back-up heater contributions.
Hence:

$$\eta_{syst} = \frac{(M_W \times L_v) + (M_g \times Cp_g \times \Delta T)}{Q_a}$$

where, $Q_a = M_a Cp_a$ ($T_{\text{into drying chamber}}$ - $T_{\text{ambient temperature}}$), ($M_a$ = 0.27 kg/s; $Cp_a$ = 1.006 KJ/kg.k, $T_{in}$ = 319.29 K $T_{amb}$ = 300.31 K); $M_w$ = mass of evaporated water (0.23 kg), $L_V$ = latent heat of vaporization (2270 KJ/Kg), $M_g$ = mass of the grains dried (4.1 kg), $CP_g$ = specific heat capacity of the grains (1676.58 KJ/Kg.k) and ΔT = change in temperature (4.6 K). Therefore the system efficiency in this set up when both sources of heat are engaged was found to be 57.7%.

**Average drying rate:** Average drying rate, $M_{dr}$, is determined from the mass of moisture removed by dryer and drying time as given by equation below, where,

$$M_{dr} = \frac{m_w}{t_d}$$

where,
$M_{dr}$ = Average drying rate, kg/h
$t_d$ = Overall drying time

Table 5: Dryer system performance

| Source of heat | Drying rate (moisture removal rate), kg/h | Dryer efficiency (%) |
|---|---|---|
| Open sun drying | 0.010 | N/A |
| Solar collector | 0.023 | 39.9 |
| Solar collector and biomass heater | 0.077 | 57.7 |

**Summary of dryer system performance:** The dryer efficiencies and drying rates of maize samples using various sources of heat is summarized in the Table 5.

The dryer system performance was found to increase when the solar collector and biomass heater was combined. The efficiency was found to be 57.7% (Table 5) this was due to the increase of the convective heat transferred associated with decrease of the system losses.

## CONCLUSION

Natural convection solar dryer, assisted with a simple biomass burner as back-up heating system was designed and fabricated. The designed dryer has a collector area of 3.77 $m^2$ and (2) drying trays with capacity to accommodate 100 kg of maize grains per batch. The other part incorporated in the design included 0.75 HP-12″ Vane axial fan to provide required air flow circulation through the system where natural convection was insufficient.

The dryer system was able to maintain consistent air temperature inside the dryer and reduced drying time significantly. The reduction in maize moisture content from 19.3-13.7% achieved by solar system alone in t 3 days of 4 h drying daily, was equivalent to the moisture content achieved using combined heating system in 3 h.

It is further evident that modern solar drying technology is faster than the open sun drying method. Thermal efficiency of the assisted solar drier was estimated to be about 57.7% with average drying rate of 0.0077 kg/h.

## REFERENCES

Ajay, C., K.S. Sunil and D. Deepak, 2009. Design of Solar Dryer with Turboventilator and fireplace. Proceeding of International Solar Food Processing Conference.

Bena, B. and R.J. Fuller, 2002. Natural convection solar dyer with biomass back-up heater. Sol. Energy, 72: 75-83.

Erastus, K., 2011. Situation analysis: Improving food safety in the maize value chain in Kenya. Report Prepared for FAO, College of Agriculture and Veterinary Science University of Nairobi.

Forson, F.K., M.A.A. Nazha, F.O. Akuffo and H. Rajakaruna, 2007. Design of mixed-mode natural convection solar crop dryers: Application of principles and rules of thumb. Renew. Energ. J., 32: 1-14.

Jindal, V.K. and S. Gunasekaran, 1982. Estimating air flow and drying rate due to natural convection in solar rice dryers. Renew. Energ. Rev., 4(2): 1-9.

Sodha, M.S., N.K. Bansal, A. Kumar, P.K. Bansal and M.A. Malik, 1987. Solar Crop Drying. CPR Press, Boca Raton, Florida, USA.

Tarigan, E. and P. Tekasakul, 2005. A Mixed-Mode Natural Convection Solar Dryer with Biomass Burner and Heat Storage Back-up Heater. ANZSES, Thailand.

Togrul, T. and D. Pehlivan, 2004. Modeling of thin layer drying kinetics of some fruits under open-air sun drying process. J. Food Eng., 65: 413-425.