

Consideration and Calculations in the design of an Auto-Regulating Solar Dryer for Variety Seedlings Production

¹Arinze W. Nwosu, ²Patricia U. Chukwu, ²Michael C. Amony

¹National Engineering Design Development Institute (NEDDI), Nnewi, National Agency for Science and Engineering Infrastructure (NASeni), the Presidency, Abuja, Nigeria.

²National Board for Technology Incubation (NBTI), Federal Ministry of Science and Technology, Abuja.

DOI: <https://doi.org/10.5281/zenodo.7552010>

Published Date: 19-January-2023

Abstract: Scarcity of seedlings of several crop varieties during each farming season, impacts negatively on agricultural production in Nigeria. Uncontrolled sun drying in the open and uncontrolled solar drying render excessive heat to the seeds thereby killing the embryo and making the seeds good for consumption only. Over the fire grate drying practiced by peasant farmers do not provide enough seeds for cultivation. The lack of technologies for commercial seedlings production is a setback to crop production in Nigeria. An auto-regulating solar dryer for variety seedlings production was designed at National Engineering Design Development Institute (NEDDI), Nnewi, National Agency for Science and Engineering Infrastructure (NASeni), the Presidency, Abuja, Nigeria. It is a requisite technology to curb excessive drying and consequent destruction of seed embryos. The automatic regulation enables the production of healthy seedlings for cultivation. Maize is employed as the grain sample in the design. The equipment can readily process other grain varieties once the requisite settings are adjusted. All aspects of engineering design as a many-sided and wide-ranging activity were covered in the holistic design but this work presents the design with pertinent considerations, constraints and calculations in the key arrears of dryer design like: air densities, drying rates, moisture content to be dried, mass and heat transfer and the quantitative determination of the solar energy to achieve drying in the area occupied by the seeds.

Keywords: Design, Dryer, Solar, Seedlings, Auto-regulating, Calculations.

I. INTRODUCTION

Figure 1 is the labelled drawing of the novel "Auto-Regulating Solar Dryer" depicting important components which include: a Heat Collector (68), Heat Sink (69) and Solar Panels (95) that generate the electricity required to drive two Blowers (29), a Hot Air Blower and a Cool Air Blower as well as two DC Motors (81) which drives Reflector Levelling Heads (83). Direct Sun rays on the Heat Collector and Heat Sink traps heat energy in the Heat Collector and Heat Sink. Apart from storing direct energy from the Sun, the Heat Sink is also thermally energized by heat energy extracted from the Sun by the Reflector through the Hot Plate. The Heat Sink releases heat stored up to augment the heat energy in the Heat Collector as needed. The Heat Sensors measure the mixed air temperature that will be used for drying in all the drying chambers. The thermostat is set to regulate the speed of the hot air blower and velocity across the delivery channels. As the temperature of the heat sink rises, so does the hot air blower speed and velocity, and similarly as the heat sinks' temperature drops, so does the blower speed and hot air velocity. The Auto Regulating System employs a programmable Arduino integrated circuit board which coordinates operations of the heat sensors, digital thermostat, accelerometer and GPS breakout boards to ensure that the Hot Air Blower takes hot air from the Heat Collector into the Drying Chamber at a rate set by the Auto Regulating

System to maintain specified drying temperature. The major parts of the solar dryer include: Drying chamber, back up heater and the airflow system.

The dryer is designed with a solar heat enhancement system in order to sustain regular heat supply under a high air velocity over a longer period of time. The system also improves heat generation when low solar heat radiation occurs. A digital thermostat system is built in other to regulate heat supply.

Maximum heat supply to the grains can be regulated as desired, either for seedlings or consumption. Therefore, fans are provided to mobilize heat generated all through the drying chambers. Also, a fresh air vent fan within the system regulate and maintain air temperature without dropping air velocity.

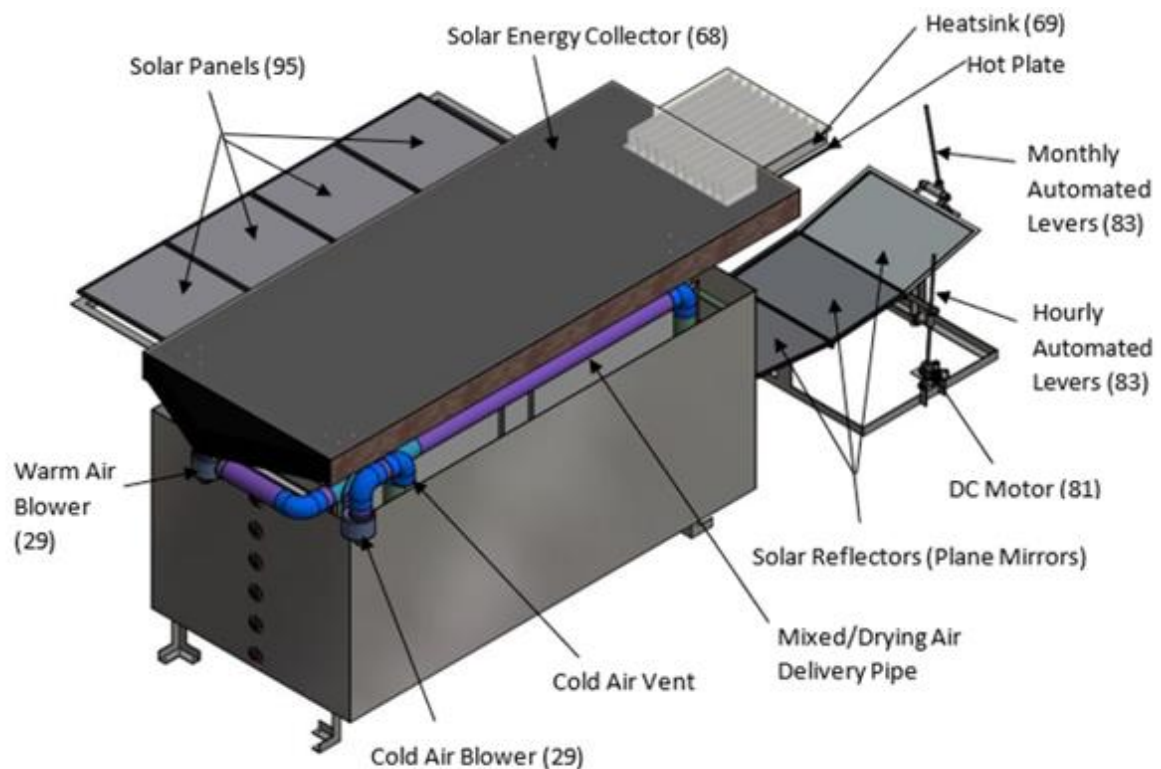


Figure 1: Auto-Regulating solar dryer

II. DESIGN CONSIDERATIONS AND CONSTRAINTS

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

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

Also, Forson et al. (2007), proposed additional design constraints applicable to natural/forced convection solar dryers based on previous research works to further assist in validating these dryer systems, some of which include:

- i. 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.

- ii. 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.
- iii. 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.
- iv. The length-to-width ratio of solar collector (L/W) for optimum performance is in the range 1-2.

III. DESIGN PROCEDURES AND EQUATIONS

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 of need (Kaduna state), the mean average day temperature for September to December is 26°C and relative humidity is 72%. Hence, from the psychrometric chart the humidity ratio is 0.015 kg_{wv}/kg_{da}. The maximum allowable drying temperature of maize grain without compromising its quality is 45°C and final moisture content of maize grain for safe storage is 13% wet basis. To carry out design calculations and size of the dryer, pertinent components which include drying chamber and back-up heater were considered. Information regarding the type of crop (maize and any other crop as the case may be) 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.

Size of the dryer chamber

The area of the drying chamber, A_{dc} , is determined from the relation:

$$A_{dc} = L \times W \quad (1)$$

Where,

W = width of the drying chamber, (m).

L = length of the drying chamber, (m).

Volume of drying chamber

$$V_{dc} = A_{dc} \times H_{dc} \quad (2)$$

Where,

A_{dc} = Area of drying chamber, (m²)

H_{dc} = Height of drying chamber, (m).

NB: The volume of drying chamber is assumed to be the maximum volume of moist air to be removed from the agricultural produce in the drying chamber.

Average drying rate

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

$$m_{dr} = \frac{M_w}{t_d} \quad (\text{Uthman et al., 2017}) \quad (3)$$

Where,

t_d = Drying time, (h)

M_w = Mass of moisture content of crop.

Density of drying air

The density of dry air can be calculated using ideal gas law, expressed as a function of temperature and pressure:

$$\rho_a = \frac{P}{R_{\text{specific}} T_a} \quad (\text{Jones 1978}). (4)$$

Where,

ρ_a = Air density (kg/m³)

P = Absolute pressure (kPa)

T_a = Absolute temperature (K)

R_{specific} = Specific gas constant for dry air (kJ/kg.K)

The specific gas constant for dry air is 0.287058 kJ/kg.K

Air vent dimensions:

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

$$A_v = \frac{V_{dc}}{V_w} \quad (\text{Al-Busoul 2017}). (5)$$

Where,

A_v = Area of the air vent, (m²)

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:

$$B_v = \frac{A_v}{L_v} \quad (\text{Al-Busoul 2017}). (6)$$

Where,

B_v = Width of air vent (m)

Volume of air to effect drying:

The volume flow rate of air V_Q (m³/h) is calculated as shown below:

$$V_Q = \frac{V_{dc}}{t_d} \quad (\text{Al-Busoul 2017}). (7)$$

Where,

V_{dc} = Quantity of moist air, (m³)

t_d = Total drying time = 6 h (a batch daily)

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

$$m_a = \rho_a \times V_Q \quad (\text{Al-Busoul 2017}). (8)$$

Where,

ρ_a = Density of drying air, (kg/m³)

V_Q = Volumetric air flow rate, (m³/h)

The quantity of heat required to evaporate the H₂O would be:

$$E = m_a(h_f - h_i)t_d \quad (\text{Al-Busoul 2017}). \quad (9)$$

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)

Solar energy

Solar irradiance is the sun's radiant power, represented in units of W/m² or kW/m². The solar constant is the average value of solar irradiance outside the earth's atmosphere, about 1366W/m². Typical peak value is 1000 W/m² on a terrestrial surface facing the sun on a clear day around solar noon at sea level, and used as a rating condition for PV modules and arrays.

$$P_I = (L_R \times W_R \times 1000)n = I \quad (\text{Tonui et al., 2013}). \quad (10)$$

Where,

P_I = Collected sun's radiant power, (W/m²)

I = Total global radiation on the horizontal surface during the drying period, in (kJ/m², kW/m²)

L_R = Length of collector, (m)

W_R = Width of collector, (m)

n = Number of collectors or reflectors

Area of Solar Collector

Total solar collector area: From the total useful heat energy required to evaporate moisture and the net radiation received by the collector, the solar drying system collector area A_c, in m² can be calculated from the following equation:

$$A_c I \eta = E = m_a(h_f - h_i) t_d \quad (\text{Tonui et al., 2013}). \quad (11)$$

Therefore, area of the solar collector is:

$$A_c = \frac{E}{I \eta} \quad (\text{Tonui et al., 2013}). \quad (12)$$

Where,

E = Total useful energy received by the drying air, (kJ)

I = Total global radiation on the horizontal surface during the drying period, (kJ/m², kW/m²)

η_c = Collector efficiency, which is assumed to be in the range of 30 to 50% (Sodha et al., 1987)

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:

- v. The depth of the drying bed, h_L, is small compared to height, H, of the hot air column

International Journal of Novel Research in Electrical and Mechanical Engineering

 Vol. 10, Issue 1, pp: (54-62), Month: September 2022 - August 2023, Available at: www.noveltyjournals.com

- vi. The whole structure is air tight and ambient air enters through the inlet and the moist warm air escapes through the exit vent (s)
- vii. 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:

$$H = \frac{\Delta P_T}{g(\rho_a - \rho^*)} = \frac{\Delta P_T R}{g \left(\frac{1}{T_{amb}} - \frac{1}{T_{dryer}} \right) P_a} \quad (\text{Tonui et al., 2013}). \quad (13)$$

Where, ΔP_T is the total pressure drop through the dryer. With the value $\Delta P_T = 6 \times 0.34 \text{ Pa}$

The amount of moisture to be removed from the product:

m_w (kg) was calculated using the following equation:

$$m_w = m_p \frac{(M_i - M_f)}{(100 - M_f)} \quad (\text{Tonui et al., 2013}). \quad (14)$$

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

Final relative humidity or equilibrium relative humidity:

ERH (%), was calculated using sorption isotherms equation given as follows:

$$a_w = 1 - \exp[-\exp(0.914 + 0.5639 \ln M)] \quad (\text{Tonui et al., 2013}). \quad (15)$$

$$m_w = m_p \frac{(M_f)}{(100 - M_f)} \quad (16)$$

$$ERH = 100a_w \quad (17)$$

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 °C (dry bulb) and a relative humidity, the psychometric chart gives a humidity ratio in (kg_{water}/kg_{d.a}). The solar collector heats air to optimum drying temperature °C (dry bulb) high than input air temperature, the humidity ratio remains constant. If passing through the grain, the moving heated air absorbs moisture until its relative humidity is equal to equilibrium relative humidity ERH (%).

From the gas laws:

$$PV = M_A RT \quad (\text{Tonui et al., 2013}). \quad (18)$$

Where,

P = Atmospheric pressure, (kPa)

V = Volume of air, (m³)

M_A = Mass of the air, (kg)

T = Absolute temperature, (K)

R = Gas constant = 0.291 kPa.m³/kg.K

Pressure drop through the drying bed:

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

$$u = a \left(\Delta \frac{P_B}{h_L} \right) \quad (19)$$

Where,

u = Superficial air velocity, (m³/h)

h_L = Drying bed thickness, (m)

a = A constant whose value is determined experimentally

Forson *et al.*, 2007 reports that for natural circulation of air through a thin layer of crop (h_L ≤ 0.20m), the value of the constant is 0.465m³/kg. Also, 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; without a heat multiplier system or solar energy concentrator. Pressure drop across the crop bed (ΔP_B) while drying on the floor is calculated using the optimum drying bed thickness of 0.2m. 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, ΔP_T = 2(ΔP_B). When all pressure drops are accounted for, experience has shown that, the gross pressure drop is about six times the value of ΔP_T (Forson *et al.*, 2007) and given by relation:

$$\Delta P_T = 6 \times (2\Delta P_B) \quad (20)$$

IV. DESIGN CALCULATIONS

Determination of Size of the dryer chamber

The size of drying is considered to be the total volume in which the agricultural materials occupied for drying, given as:

From eq (1), $A_{dc} = L \times W$

L = 1.3m; W = 1.5m; H = 0.13m; number of drying chambers = 12

The total area of drying chamber is

$$\therefore A_{dc} = 1.3 \times 1.5 \times 12 = 23.4 \text{ m}^2$$

The area of the drying chamber is 23.4m²...

The total volume of moist air assumed in the drying chamber is given as

From eq (2), $V_{dc} = A_{dc} \times H_{dc}$

$$\therefore V_{dc} = 23.4 \times 0.13 = 3.042 \text{ m}^3$$

International Journal of Novel Research in Electrical and Mechanical Engineering

Vol. 10, Issue 1, pp: (54-62), Month: September 2022 - August 2023, Available at: www.noveltyjournals.com

The volume of the drying chamber is 3.042m^3

Determination of average drying rate

From eq (3), $m_{dr} = \frac{A_{dc}}{t_d}$; Take $t_d = 6\text{h}$ daily;

$$\therefore m_{dr} = \frac{23.4}{6} = 3.9 \text{ m}^2/\text{h}$$

The average drying rate is $3.9\text{m}^2/\text{h}\dots$

Determination of density of drying air

The density of drying air is determined by the drying air temperature was taken to be the maximum allowable temperature for drying seedlings

From eq (4), $\rho_a = \frac{P}{R_{\text{specific}} T_a}$, Take $T_a = 42^\circ\text{C} = 315.15\text{K}$; $R_{\text{specific}} = 0.287058 \text{ KJ/Kg.K}$

$$\therefore \rho_a = \frac{101.325}{0.287058 \times 315.15} = 1.12 \text{ Kg/m}^3$$

The density of the drying air, say $1.12\text{Kg/m}^3\dots$

Determination of air vent dimensions

The area of the air vent is determined by the drying air speed going into the chambers. Take $v_w = 1.8 \text{ m}^2/\text{s}$

From eq (5) $A_v = \frac{V_{dc}}{V_w}$,

$$\therefore A_v = \frac{3.042}{1.8} = 1.62\text{m}^2$$

The air vent of the dryer, say 1.62m^2

Determination of air volume to effect drying

The maximum volume flow rate of assumed moist air to be removed daily is determined by the period drying is affected. Take $t_d = 6\text{h}$.

From eq (7) $V_Q = \frac{V_{dc}}{t_d}$,

$$\therefore V_Q = \frac{3.042}{6} = 0.507 \text{ m}^2/\text{h}$$

The volume flow rate of assumed moist air for drying, say $0.507\text{m}^2/\text{h}\dots$

Determination of mass flow rate of moist air to effect drying

Mass flow rate of moist air, m_a , kg/h was calculated as

From eq (8) $m_a = \rho_a \times V_Q$

$$\therefore m_a = 1.12 \times 0.507 = 0.56784 \text{ Kg/h}$$

The mass flow rate of the assumed moist air for drying, say $0.56784 \text{ Kg/h}\dots$

Determination of Solar energy to effect drying

Solar energy collected by a solar energy concentrator for a clear atmosphere is determined the total global solar radiation at 1kW/m^2 . Take, $L_R = 0.7\text{m}$; $W_R = 1\text{m}$; $n = 3$

From eq (10) as $P_I = (L_R \times W_R \times 1000)n = I$

$$\therefore P_I = (0.7 \times 1 \times 1000) \times 3 = 2100 \text{ W/m}^2$$

The power received by the heat concentrator for drying = 2.1kW/m^2 .

V. CONCLUSION

The work has presented the procedure and the relevant equations and relationships for the determination of solar dryer chamber size, average drying rate, density of drying air, the air vent dimensions, air volume to effect drying, mass flow rate of moist air to effect drying as well as the determination of solar energy required per metre square to dry the seeds to the required moisture content. The total drying area is 23.4 m^2 , average drying rate is $3.9 \text{ m}^2/\text{h}$ while the power received by the heat concentrator is 2.1 kW/m^2 . It is hoped that this innovation will be proliferated to ensure the production of seedlings and enhance crop productivity in Nigeria.

REFERENCES

- [1] Al-Busoul M. (2017). Design of Fruits Solar Energy Dryer under Climatic Condition in Jordan. Journal of Power and Energy Engineering, 5, Pp 123-137 ISSN: pp. 2327-5901.
- [2] Jones F. E. (1978). The Air Density Equation and the Transfer of the Mass Unit. Journal of Research of the Notional Bureau of Standards, Vol. 83; No. 5, p. 419.
- [3] Tonui K. S., Mutai E. B. K, Mutuli D. A., Mbuge D. O. and Too K. V. (2013). Design and Evaluation of Solar Grain Dryer with a Back-up Heater. Res. J. App. Sci. Eng. Technol., 7(15): pp. 3036-3043.
- [4] Uthman, F., Balogun, A.L and Onipede, E.A (2017). Design, Fabrication and Testing of a Biomass Dryer. Journal of Research and Development Studies Vol. 5. No. 1.