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Determination of Energy Requirement for the Design of a 250 kg Capacity Tray Dryer for Instant Pounded Yam Flour

J. O. Adekunle[1], Bayode J. Olorunfemi[2]
[1] Raw Materials Research and Development Council, Abuja, Nigeria
[2]Department of Mechanical Engineering, Federal University Oye, Nigeria

Abstract

The determination of energy requirement for the design of a 250kg/hr capacity Tray Dryer for drying of pounded yam flour was carried out. The design parameters considered were; the rate of drying, the dry- bulb temperature, relative humidity, velocity of the air, the surface heat transfer coefficient and the properties of the yam (the moisture content, surface- to-volume ratio and the surface temperature and the rate of moisture loss). It also considers the heat and mass balance in an ideal dryer, heat and mass balance in a Tray Dryer. Laboratory data with assumptions on the yam thickness, initial and final moisture level and the design capacity which were used to calculate the amount of water to be removed which is put at 700kg was also calculated. The airflow into the dryer and the outlet humidity of drying air were calculated as 8312.5kg of dry air/hr. and 0.15kg of water/kg of dry air respectively. The psychometric properties of drying air properties were determined; the drying rate was calculated to be 0.002kg/s, drying time as 3.1hr while the total heat input per hour requires for drying was calculated to be 53.33kJ/hr. (14.81kW). This was multiplied by safety factor of 1.2 which brings the total heat required to 18kW. In view of this, 20kW rating heating element was chosen to provide the required energy for a Tray Dryer that would produce 250kg of instant pounded yam flour per hour.

Key Words: Yam, drying rate, surface temperature, psychometric properties

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I. INTRODUCTION

Yam tuber is the main part of the yam plant which has high carbohydrate content, low in fat and protein;and provides a good source of energy, sweet in flavour, consumed as boiled yam, often pounded into a thick paste after boiling and consumed with soup [1]. It is also processed into flour for use in the preparation of the paste and instant pounded yam. Its medicinal use as a heart stimulant is attributed to its chemical composition, which consists of alkaloids of saponin and sapogenin. Its use as an industrial starch has also been established as the quality of some of the species is able to provide as much starch as in cereals [2, 3].

Nigeria is the world's largest producer of yams, accounting for over 70–76 percent of the world production. According to the Food and Agriculture Organization report, 1985, Nigeria produced 18.3 million tonnes of yam from 1.5 million hectares, representing 73.8 percent of total yam production in Africa [2]. According to 2008 figures, yam production in Nigeria has nearly doubled since 1985, with Nigeria producing 35.017 million metric tonnes with value equivalent of US$5.654 billion [3]. In perspective, the world's second and third largest producers of yams, Côte d'Ivoire and Ghana, only produced 6.9 and 4.8 million tonnes of yams in 2008 respectively. According to the International Institute of Tropical Agriculture, Nigeria accounted for about 70 percent of the world production amounting to 17 million tonnes from land area 2,837,000 hectares [3, 4].

However, yam processing is a relatively small industrial activity. Industrial activities in this area are predominantly in the informal sector, where tubers are parboiled and sun-dried into chips, which are later processed into flour. Yam flour apart from serving as an outlet for preservation of yam has the possibility of making yam products always available.

The market for instant pounded yam flour in Nigeria is very wide. Major users of the products includes households, hotels, restaurants, food vendors, starch derivatives factories etc. and for exports. A Post harvest loss in yam due to its seasonal nature is a major problem in the market supply chain of small farm holders in Nigeria. Drying is one of the effective post-harvest technologies used for making powders of long shelf life [2].

A Tray Dryer is equipment used in drying or dehydration. Drying or dehydration is defined as the application of heat under controlled condition to remove the water normally present in tubers such as yam by evaporation[5]. The main purpose of dehydration is to reduce the moisture content thereby extending the shelf life of the yam. The reduction in weigh and bulk of food reduces transportation and storage cost and also provides greater variety and convenience for the consumers.

II. MATERIALS AND METHODS

Materials

1. 250kg capacity Tray Dryer
2. Yam Tuber with the following laboratory data and assumptions

i. Average diameter of yam tuber = 50mm
ii. Thickness of the sliced yam tuber = 5mm
iii. Yam initial moisture content = 75%
iv. Yam final moisture content = 5%
v. Specific Capacity (Cps) of yam = 1.465kJ/kgK
vi. Design capacity = 250kg of slicesdried yam /batch
vii. $Q_1 = Q_L = 0$ = (no heat loss)
viii.. Initial Yam temperature (T_S) = 30^0C
ix. Final temperature of Yam (T_{S2}) = 70^0C

III. Methods

Mechanism of Drying

The design was carried out based on the mechanism of drying sliced yam tuber. When hot air is blown over sliced yam, heat is transferred to the surface, and latent heat of vaporization causes water to evaporate. Water vapour diffuses through a boundary film of air and carried away by moving air. This creates a region of low vapour pressure at the surface of the yam, and a water vapor pressure gradient is established from the moist interior of the yam to the dry air. This gradient provides the driving force for water removal from the yam. Water moves to the surface by the following mechanisms [6]:

- Liquid movement by capillary force
- Diffusion of liquid that is adsorbed in layers at the surface of the yam
- Water vapor diffusion in the air space within the yam which causes vapor gradient.

When yam is placed into the dryer, there is short initial settling down period as the surface heats up to the wet-bulb temperature. Drying then commences and provided that water moves from interior of the yam at the same rate as it evaporate from the surface, the surface remains wet. This is known as **the constant rate period**[6]and continues until certain critical moisture content is reached. The three characteristics of air that are necessary for successful drying in the constant rate period are:

- A moderately high dry-bulb temperature
- A low relative humidity (RH)
- A high air velocity

When the moisture content of the yam falls below the critical moisture content, the rate of drying slowly decreases until it approaches zero at the equilibrium moisture content (that is the yam come into equilibrium with the drying air). This is known as **falling rate period.** During the falling rate period the rate of water movement from the interior of the yam to the surface falls below the rate at which water evaporates to surrounding air, the surface then dries out [6].

Determination of Design Parameters

The rate of drying depends on the properties of the dryer (the dry- bulb temperature, relative humidity, velocity of the air, the surface heat transfer coefficient and the properties of the yam (the moisture content, surface- to-volume ratio and the surface temperature and the rate of moisture loss).

Other factors, which influence the rate of drying include:

i. Flow Process for Instant Pounded Yam flour

Industrial processing of yam tubers into instant pounded yam flour involves the following processes: peeling, washing, parboiling, drying, milling and packaging. However, a parboiled yam is known to contain a lot of water, which are surface and bond water, these waters must be promptly removed to obtain a product of desirable properties, hence the need for proper drying.

ii. Design Consideration

The design of a Tray Dryer took into consideration the heat and mass balance in ideal dryer according to laboratory data and assumptions, the psychometric air properties as well as the heating system.

Design Calculations

Heat and Mass Balances in an Ideal Dryer

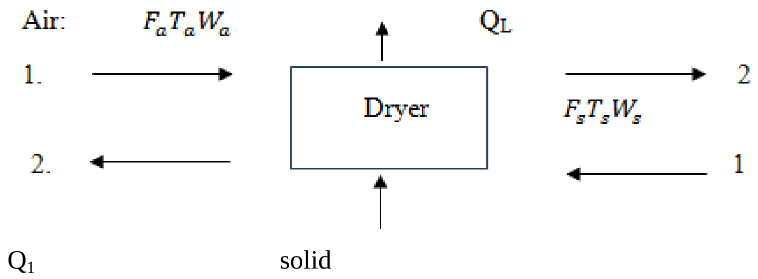

Fig 1: An Ideal Dryer process

The material balance on the moisture is expected as [1] :

$$F_a W_{a1} + F_s W_{s1} = F_a W_{a2} + F_s W_{s2} \qquad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

And the heat balance on the dryer is

$$Q_1 + F_a H_{a1} + F_s H_{s1} = Q_L + F_a H_{a2} + F_s H_{s2} \qquad \ldots\ldots\ldots\ldots.. \quad (2)$$

Enthalpy of the air and solid is expressed respectively as

$$H_{a1} = C_s (T_a - T_0) + \lambda_0 \qquad \ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$H_{s1} = C_{ps} (T_s - T_0) + C_{pa} (T_s - T_0) \qquad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

Where:

F_s = Solid feed rate, (kg of dry solid/hr.)
W_{s1} = Moisture content of solid at stage 1
T_{s1} = Inlet Temperature of solid at stage 1, (^{0}C)
W_{s2} = Moisture content of solid at stage 2
T_{s2} = Temperature of solid at stage2 (^{0}C)
F_a = Air flow rate (kg of dry air/hr.)
T_{a1} = Inlet air Temperature (^{0}C)
W_{a1} = Inlet air absolute humidity (kg of watering of dry air)
T_{a2} = Outlet air Temperature (^{0}C)
Q_1 = Heat added to the dryer from any other external source, (J/s)
Q_L = Heat loss, (J/s)
H_{a1} = Enthalpy of air, (kJ/kg)
H_{S1} = Enthalpy of solid at stage 1
H_{S2} = Enthalpy of the solid at stage 2
C_{ps} = Heat capacity of the solids, (KJ/kgK)
W_{a2} = Outlet air humidity
C_{pa} = Heat capacity of liquid moisture (4.187 KJ/kgK)
C_s = Humid heat of the air – water mixture
T_0 = Reference Temperature which is usually taken as 0^0C
λ_0 =Latent heat of Evaporation

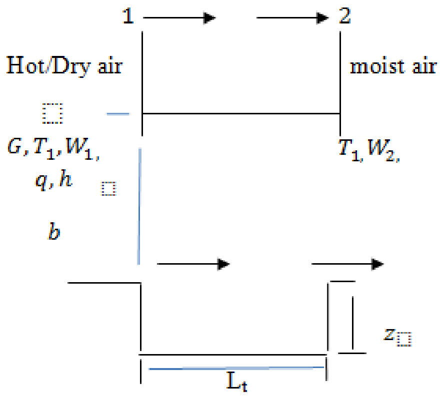

Fig 2: Heat and mass balance variables in Tray Dryer

L_t = Length of Tray, (m)
T = Temperature (^{0}C)
W = air humidity
G = dry air flow, (kg/s.m^2)
b = distance between Tray, (m)
h = heat transfer coefficient, (Wm^{-2}k^{-1})
z = width of the Tray, (m)
q = heat flux, (kJ/s)
C_s = humid heat of the air-water mixture

The heat balance over a length dL_t of a Tray for any section with a width dimension Z is expressed according to[7] as:

$$dq = GC_s(z.b)dt \qquad \ldots\ldots\ldots.\ldots\ldots \quad (5)$$

Expressing dq in terms of convective heat transfer

$$dq = h(z.dL_t)(T - T_w) \qquad \ldots\ldots\ldots\ldots\ldots \quad (6)$$

Where:
h = heat transfer coefficient, (Wm $^{-2}$k^{-1})
T_w = wet bulb temperature, (^{0}C)
L_t = length of the Tray, (m)

Assumption:

It is assumed at this stage that the heat transfer coefficient (h) and the humid heat of the air-water mixture (C_s) are constant.

Equation (5) and (6) can be re-arranged and integrated as:

$$\frac{hL_t}{GC_s b} = \frac{T_1 - T_w}{T_2 - T_w} \qquad \ldots\ldots\ldots\ldots\ldots..\ldots \quad (7)$$

Where:
T_1 = inlet temperature (^{0}C)
T_2 = outlet temperature (^{0}C)

$$(T - T_w) = \frac{(T_1 - T_w) - (T_2 - T_w)}{\ln\left(\frac{T_1 - T_w}{T_2 - T_w}\right)} \qquad \ldots\ldots\ldots\ldots\ldots.. \quad (8)$$

Combining equation (7) and (8), we have

$$(T - T_w) = \frac{\left[(T_1 - T_w) - (1 - \exp\left(\frac{-hL_t}{GC_s b}\right)\right]}{\left(\frac{-hL_t}{GC_s b}\right)} \qquad \ldots\ldots\ldots.\ldots. \quad (9)$$

The constant rate period drying time can be represented as stated by [3]

$$t_0 = \frac{X\rho_s L_t \lambda w(W_{s1} - W_{sc})}{GC_s b(T_1 - T_w)[1 - \exp(-hL_t)]/(GC_s b)} \qquad \ldots\ldots\ldots\ldots.. \quad (10)$$

Where
W_{s1} = the initial moisture content of the product
W_{sc} = critical moisture content
X = thickness of the product (Yam) in the Tray
ρ_s = solid bulk density
λ_w = latent heat at T_w

[7]also developed a time expression for the fallen rate as:

$$R = \frac{-F_s dx}{Adt} \qquad \ldots\ldots\ldots\ldots..(11)$$

$$R = \frac{h}{\lambda(T_1 - T_w)} \qquad \ldots\ldots\ldots\ldots.(12)$$

Combining and integrating (11) and (12)

$$T = \frac{F_s \lambda_w (X_1 - X_2)}{A_h (T - T_w)} \qquad \ldots\ldots\ldots\ldots \quad (13)$$

Substituting $T - T_w$ in equation (9) into equation (13), the falling rate period time can be expressed as:

$$t_f = \frac{\left[X \rho_s L_t \lambda_w X_c \ln\left(\frac{W_c}{W}\right)\right]}{\left[G C_s b (T_1 - T_w)\left(1 - exp\left(\frac{-h L_t}{G C_s b}\right)\right)\right]} \qquad \ldots\ldots\ldots\ldots\ldots \quad (14)$$

Where, $\frac{W_c}{W}$ is the diffusion coefficient. Equation (10) and (13) take into account the difference between the constant rate and the falling rate periods. The total drying time can be expressed as the sum of both drying times.

IV. RESULTS AND DISCUSSION

Results

Numerical Calculations of Design Parameters

A. 700kg of water to be removed from the yam to get an equivalent amount of dry matter in 250kg of parboiled yam slices at 5% wet basis (wb) moisture content was calculated thus:

Equivalent Amount of dry matter in Yam = $250Kg\ (1 - \frac{5}{100})$ = $250\text{kg}\ (1 - 0.05)$

$= 250\text{kg}\ \times 0.95$

$= 237\text{kg}$

The Initial weight or feed rate of Yam (F_s) $= \frac{237.5}{1 - 0.75}$

(F_s) $= 950\text{kg}$

Final weight of yam $= 250\text{kg}$

Amount of water to be removed = (950-250) kg

=700kg

The material balance on the moisture using equation (1)

$$F_a W_{a1} + F_s W_{s1} = F_a W_{a2} + F_s W_{as}$$

$$F_a (0.70) + 950\ \times 0.75 = F_a W_{a2} + 950\ \times 0.05$$

$$F_a = -\frac{665}{(0.07 - W_{a2})} \qquad \ldots\ldots\ldots\ldots \quad (15)$$

The heat balance for the Dryer is calculated using equation (2), (3) and (4)

$$Q_{1=} F_a H_{a1} + F_s H_{s1} = Q_L + F_a H_{a2} + F_s H_{s2}$$

$$H_{a1} = C_s (T_a - T_0) + \lambda_0$$

$$C_s = C_{air} + W C_{water}$$

$\lambda_0 = 250kg$ of water [6]

$C_s = 1.005 + W(1.884) kJ/kg$ of dry air

The Heat balance for the air is also calculated as:

$$H_{a1} = [1.005 + 0.34 \times 1.884] + (80 - 0)(0.34 \times 2501.4)$$

= 170.57kJ/Kg of dry air

$$H_{a2} = [1.005 + 1.88 W_{a2}] \times [40 - 0 + (W_{a2} \times 2501.4)]$$

= 40.2 + 2576.6W_{a2}kJ/kg of dry air

Heat balance for solid:

$$H_{s1} = Cp_s (T_s - T_0) + W Cp_a (T_s - T_0)$$

$$H_{s1} = 1.465(35 - 0) + (0.75 \times 4.187)(35 - 0)$$

= 51.275 +109.91

= 161.184kJ/kg of dry solid

$$H_{s2} = 1.465(70 - 0) + (0.05 \times 4.187)(70 - 0)$$

= 117.205kJ/kg of dry solid

The value for H_{s1} and H_{s2} can be replaced in equation (2) for heat balance

$$F_a \times 170.57 + 950 \times 161.18 = F_a (40.20 + 2576.6 W_{a2}) + 950 \times 117.205$$

$$170.57 F_a - 40.20 Fa - 2576.6 W_{a2} F_a = 111{,}344.75 - 153{,}121$$

$$F_a(170.57 - 40.20 - 2576.6W_{a2}) = -41{,}776.25$$

From equation (15)

$$F_a = -\frac{665}{0.07 - W_{a2}}$$

Substituting for F_a and solving the mass and heat balance equation simultaneously:

$W_{a2} = 0.15$kg of water/kg of dry air

Substituting for Wa_2 above

$F_a = \quad 8312.5Kg$ of dry air / hr.

The air flow into the dryer = 8312.5kg of dry air/hr.

The outlet humidity of drying air = 0.15kg of water/kg of air

Psychometric Chart Reading

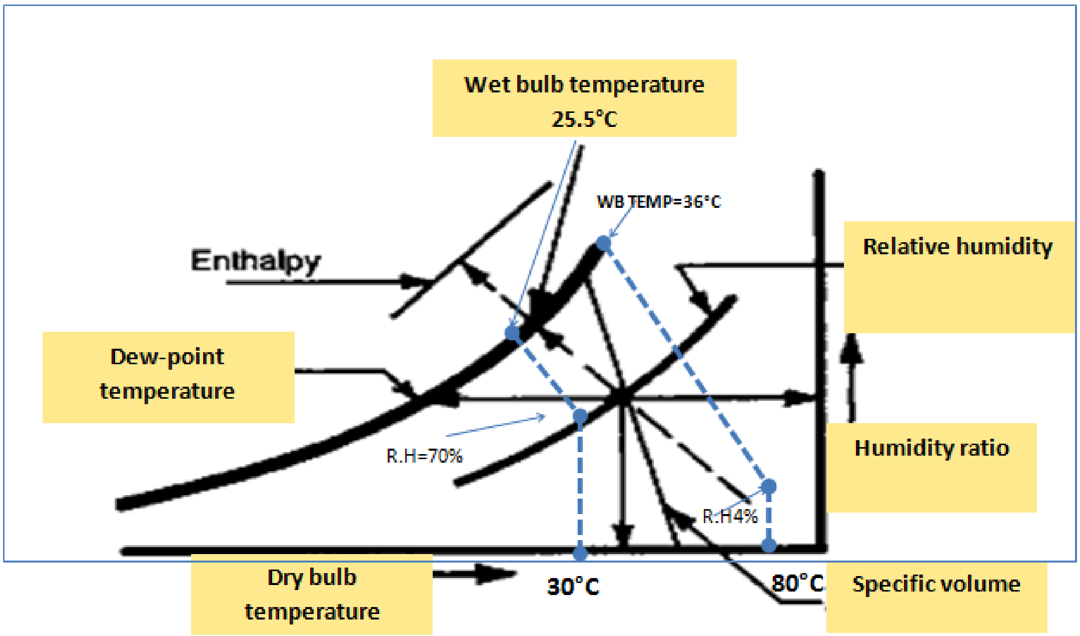

Fig. 3: CIBSE Psychometric Chart Based on a Barometric Pressure of 101.325kPa[8]

Summary of Drying Air Properties based on Psychometric Chart Reading

Stage 1

Dry bulb temperature = 30°C

Ambient Relative humidity = 70%

Enthalpy = 80kJ/kg

Moisture content = 0.0194kg/kg (dry air)

Wet bulb temperature = 25.5°C

Specific Volume = $0.75m^3/kg$

Stage 2

Dry Bulb temperature = 80°C

Wet bulb temperature = 36°C

Enthalpy = 28kJ/kg

Relative humidity = 4%

Specific volume = $1.30m^3/kg$

Dew point temperature = 49°C

From Fig. 2 above the effective area covered by yam slices in the Tray

$A_T \quad = \quad L_t.z$ ---------------------- (16)

$A_T \quad = \quad (0.4x0.9)\ m^2$

$\quad = \quad 0.36m^2$

For a Tray of food, in which water evaporates only from the upper surface, the drying time is found using [6].

$$m_c = \frac{h_c}{\lambda}(\theta_a - \theta_s) \qquad \text{-------------- (17)}$$

Where,

$h_c =$ Surface heat transfer coefficient ($Wm^{-2}k^{-1}$)
$\theta_a =$ Dry bulb temperature of air (^oC)
$\theta_s =$ Wet bulb temperature of solid
$\lambda =$ Latent heat of evaporation at the wet bulb temperature (J/kg)
$m_c =$ Drying rate ($kg\ s^{-1}$)

For a parallel air flow according to [2]:

$h_c = 14.3G^{0.8}$

Where,

G = mass flow rate, (kg/ms)
= F_a(kg/hr.)

$$= \frac{8312.5kg}{3600 \times 0.9}$$

$$= 2.566\text{kg}/ms$$

$$h_c = 14.3G^{0.8}$$

$$= 14.3 \times (2.566)^{0.8}$$

$$= 30.39Wm^{-2}k^{-1}$$

$$m_c = h_cA\left(\frac{\theta_a - \theta_s}{\lambda}\right)$$

$$= 30.39\left(\frac{80-36}{2.3 \times 10^6}\right)$$

$$= 0.002\text{kg/s}$$

Using equation (10) above, drying time constant rate period is calculated as

$t_0 = 4320s = 1.2hr$

Using equation (14), the falling rate is calculated as:

$t_f = 7000s = 1.9$ hrs.

Total drying time:

$t = t_f + t_0$ --------------------- (18)
$= 1.9 + 1.2 = 3.1$ hrs
= 3hr 6min

Design of the Heating System

Using the psychometric chart according to [8] for an ambient air at 30^{o}C dry bulb temperature and 70 percent relative humidity, the enthalpy is 80kJ/kg and specific volume is $0.75m^3$/kg. This same air is heated to 80^{o}C for drying. By locating point (1) and (2) on the chart, the heat content at point (2) is 280kJ/kg, its relative humidity of 4 percent and humid volume of $1.3m^3$/kg.

The airflow rate through the heating section is $200m^3$/hr.

Total air moved per hour $= \left(\frac{200m^3}{hr}\right) \div \left(\frac{0.75m^3}{kg}\right)$ ---------------------- (19)

$$= \frac{200}{0.75}\frac{\text{kg dry air}}{\text{hr}}$$

$$= 266.67\text{kg/hr}$$

Total heat input per hour $= 236.67\ \frac{kg}{hr}$ dry air $\times\ \frac{200kg}{\text{kg dry air}}$ ----------------------- (20)

$= 53.33kJ/hr = 14.8kW$

Multiplying by safety factor of 1.2

Total heat required $= 18kW$

As a result of 18kW heat requirement, a **20kW** rating-heating element was chosen.

V. Discussion

The numerical calculations of the design were carried out wherein the equivalent amount of dry matter in the yam was calculated to be 237kg and the final weight was 250kg,the amount of water removed from the yam was determined as 700kg. The air flow into the dryer was calculated to be 8312.5kg of dry air/hr while the outlet humidity of drying air was 0.15kg of water/kg of air.

The total drying time and heating requirement of the dryer were arrived at by using some extracted data from [8] to compute the parameters.Atmosphere air at stage 1 having a dry bulb temperature of 30^oC and 70% relative humidity (Rh) is passed through heating coil where adiabatic heating takes place. The dry bulb temperature increases without any increase in absolute humidity, the relative humidity (Rh) at stage 2 is lower than stage 1. The heated air is forced through the yam slices in the tray to absorb moisture. Sensible heat is converted to latent heat to evaporate the moisture. The total drying time was computed to be 3hr 6minutes while the energy requirement to dry 250kg of raw yam was calculated to be 18kW hence 20kW heating element rating was chosen.

VI. CONCLUSION

The total heat input per hour was calculated to be 14.8kW. Making provision for safety requires that thecalculated figureshould bemultipliedby a factor of safety of 1.2 which gave 18kW as the total energy required. However, electrical element standard ratings are in the range of 5kW, 10kW, 15kW, 20kW, 25kW etc. hence the nearest ratings to 18kW is 20kW. Therefore, 20kW rating heating element will be required to provide the needed energy required for the design of a dryer of 250kg per hour capacity instant pounded yam flour.

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