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Simulation of the Effects of Tray Dryer Parameters on Plantain Drying Process Using Matlab

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ABSTRACT*:* *Tray dryers remain the most extensively used dryers because of their simplicity and economic design. Optimal tray dryer design involving the determination of its optimum operating parameters may eliminate or reduce non-uniformity of drying and increase dryer efficiency. This paper investigates the effects of dryer parameters on one another and the plantain drying process by simulating the parameters of a tray dryer in order to evaluate effects of major decision variables including temperature, time, fan efficiency and air quantity controlled by the ratio of the heater housing area to the cabinet area. The design equation of a tray dryer was programmed to give various output based on changes in the input parameter for 2600Kg of plantain in a M-Function File environment using matlab software. It was observed that temperature has the greatest effect on the drying process and with other parameter kept constant, achieving drying of a material at a higher temperature implies higher cost of fuel generation and lower cost of fan, while achieving drying at an earlier time implies higher cost of power and fan. Similarly, an increase in the ratio of the heater housing area to the cabinet housing area led to a lower cost of fan and vice versa, while fan's efficiency has only influence on the cost of the fan.*

KEYWORDS - *design parameters, drying temperature, matlab, simulation, tray dryer*.

1. INTRODUCTION

Removal of water present in solid materials up to a certain level for bone-dried products has ever been a matter of concern in food preservation and pharmaceutical industries. This is necessitated by the fact most microorganisms/ enzymes causing spoilage are rendered incapable under dehydrated conditions. As a consequence, for the wide variety of available dehydrated food and related products there exists an ever-growing concern for meeting quality specifications and conserving energy. This in turn necessitates a thorough understanding of the drying operation and solution of the problems related to the design and operation of dryers.

Among the several alternatives available for drying food products such as using fluidized bed, spray dryer, drum dryer, and tray (cabinet) dryer with their enormous applications and countless drawbacks, particular emphasis has been placed on tray dryers because of the advantages of simplicity and design economy. The drying medium in these dryers is hot air or combustion gases coming from a furnace, which makes them adaptable to the drying of almost any material that can be put in a tray. The operation of a tray dryer is simple compared to other dryer types and do not require any formal training as the majority of farmers involved in the production reside in rural areas where unskilled labour is predominant. In case of breakdown, all the parts of a tray dryer can be manufactured locally and within the country as compared to spray dryers and some others which require some imported parts, causing unnecessary delay in production. Many of the dryer types apart from fluidized bed and tray dryer operate at temperatures greater than 75°C thereby producing only pre-gelatinized plantain flour. On the other hand, cabinet (tray) dryer can operate at variable temperature producing both pre-gelatinized and gelatinized plantain flour which of course is an advantage to producers rather than having two different dryers for the two flour types. The fluidized bed in this instance was not being an option due to its susceptibility to collapsing, especially when heavier sizes are introduced. In addition, the tray dryer handles wider range of materials compared to other dryer types. Sometimes, these farmers also farm other product (mixed farming) and would also desire to process or preserve them through drying. Hence tray dryer is a multipurpose dryer to dry different farm produce [1 – 4].

Drying as a method of preserving agricultural produce is not only limited to plantain but also applicable to other food stuffs numerous to mention. Moreover, many business men and women are willing to invest in the flour business which is a booming business all over the world especially in Africa where various agricultural products like yam, cassava and plantain flour are major forms of flour consumed in addition to some others like corn flour, wheat flour and others which are essential in the baking industries. In particular, plantain is a staple carbohydrate food grown mostly in the southern part of Nigeria and in the tropical region of the world. In south western Nigeria, plantain is chipped, dried and milled into fine powder known as plantain flour processible in hot water above 80°C to produce plantain "fufu", a dough that is much comparable to those made from yam and cassava, which are among the most highly consumed staple foods. The meal is gaining particular attention due to recent discoveries on its ability to lower blood sugar and uses as a readily available medicine for diabetes [5]. Since plantain has high moisture content, the chips are subjected to drying traditionally using heat from sun but this method requires much time which may result to spoilage, organism attack as well developing off- flavor on storage after drying. Because of these problems, there is need to develop an effective drying technology to convert the product into stable form for industrial and export purposes [3,4].

Generally, with respect to the rate and total drying time, dryer performance is dependent on the factors such as characteristics of air, product characteristics and equipment characteristics. Despite the many commercially available drying techniques at present, fruits and vegetables are still processed by the method of hot air drying largely because it is the simplest and most economical. Although there are other moisture/liquid removal processes such as settling, filtration, super critical extraction, centrifugation etc. where the liquid/moisture is removed by mechanical means with significant amount of moisture still retained in the material. This remaining moisture/liquid is removed by drying. One example is in the production of condensed milk which involves evaporation while the production of milk powder involves drying.

Four major factors of a tray dryer are surface area of material, air humidity, temperature and quantity of air [6,7]. However, from design equation of a tray dryer, its parameters are temperature, time, fan efficiency and the quantity of air which is controlled by the ratio of the heater housing area to the cabinet area. Drying ought to be controlled because of the valuableness and susceptibility of food to spoilage. Drying food very slowly, gives opportunity for microorganisms to grow and cause food spoilage or poisoning or even makes the food not saleable. When foods are not saleable, then profit and money are lost. On the other hand, fast drying can cause loss of quality, such as nutritional value, colour and flavour. Therefore, a balance should be made between obtaining the highest material quality and lowest cost.

As pointed out earlier, of the four factors of a tray dryer, the last three factors of a tray dryer relate to the drying air and not all the factors really affect the optimization of a tray dryer as temperature is the most effective way of controlling the other two factors [7]. However, for a tray dryer, there are four main parameters that influence its optimization (in terms of quality of product, operation and configuration) of a tray dryer. These are: time, dimensions (area) of the heater housing and the drying house, efficiency of the industrial fan and drying temperature. The quality of any material to be dried using a tray dryer all depend on these factors. Since simulation entails various changes in some input parameters concurrent observation of simultaneous changes in other variable it was therefore needful to program the entire design equation of a tray dryer in a matlab environment for quick synthesis and tabulation.

A considerable number of research works has been done regarding the design of tray dryers using various design approaches [1 – 4, 6 – 14]. Bertin and Blazquez [15] presented a mathematical model for a tunnel dehydrator, of the California type, for plum drying, and searched for the optimum capacity of the dryer. A mathematical model for the semi-batch operation of industrial dryers with trucks and trays had been reported and analysed by Kiranoudis et al. [4]. Design aspects were discussed concerning problems involving both single dryer and systems of parallel dryers. In both cases, optimum ftowsheet configuration and operation conditions were sought and verified by appropriate formulation of design and optimization strategies. Very recently, Watharkar et al. [1] investigated thin layer drying of Bhimkol pulp in a hot air dryer at 40°C, 50°C and 60°C respectively and used a general drying code developed in MATLAB R2014a to study the drying kinetics. Despite the obvious importance of deriving design methodologies in this field, limited efforts are cited in the literature. However, no work was found regarding matlab simulation of a tray dryer design parameters. Therefore, the aim of this work is to adapt the entire design equation of a tray dryer in a matlab environment for quick synthesis and simulation in order to determine the effects of each parameter on one another and the drying process using plantain as a case study.

NOTATIONS

M_{bd}	=	Mass of bone dry sample
M_{WF}	=	Mass of wet feed
M_r	=	Moisture content removed in percentage
T_{Fa}	=	Reference temperature of feed
M_p	=	Mass of plantain = M_{bd}
C_{pp}	=	Specific heat capacity of plantain at constant pressure
T_v	=	Vaporization temperature
C_{pw}	=	Specific heat capacity of water at constant pressure
T_b	=	Final temperature T_v
M_{TW}	=	Total mass of water in the feed
ΔH_v	=	Heat of vaporization of water
M_{WL}	=	Mass of water left in the sample
M_{wr}	=	Mass of water removed
M_c	=	Moisture content
M_d	=	Mass of dry sample
X_c	=	Mass fraction of carbohydrate
X_p	=	Mass fraction of protein
X_f	=	Mass fraction of fat
X_a	=	Mass fraction of ash
X_w	=	Mass fraction of water
Q_L	=	Heat loss
h	=	Convective heat transfer coefficient
σ	=	Stefan-Boltzmann constant
K	=	Thermal conductivity
dx	=	Thickness available for heat transfer
A	=	Surface area
C_1, C_2, C_3, C_4, C_5	=	Constants
T	=	Temperature in Kelvin
T_r	=	Reduced temperature
T_c	=	Critical temperature
M	=	Molecular weight
Q	=	Power
t	=	time
M_{air}	=	Mass flow rate of air
Q_T	=	Total power
Cp_{air}	=	Specific heat capacity of air
ΔT	=	Temperature difference
$\overline{V}_{air}$	=	Specific volume of air
V_{air}	=	Volumetric flow rate of air
μ_1	=	Velocity of heater housing
μ_2	=	Velocity of drying chamber
A_1	=	Cross sectional area of heater housing
A_2	=	Cross – sectional area of drying chamber
ΔP = hair	=	Pressure head loss of air
f	=	Friction factor
L	=	Length
D_h	=	Hydraulic diameter
A_c	=	Cross sectional area
μ_A	=	Velocity (Average)
Red	=	Reynolds' number
ε/D	=	Relative roughness
g	=	Acceleration due to gravity
V_k	=	Kinematic viscosity
h_w	=	Head loss for water
$\int_w$	=	density of water
H_{HH}	=	Head loss of heater housing
H_L	=	Head loss
K_L	=	Constant
H_{TL}	=	Total head loss
H_M	=	Head loss of material

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2. THEORETICAL BACKGROUND AND DESIGN EQUATION DEVELOPMENT

The tray dryer considered in this study uses a configuration typical for a number of industrial applications with semi-batch operating trays. Air is blown over the trays containing particles of the product being dried, which are evenly distributed on the surface of each tray such that the product has uniform moisture content upon drying.
Recirculated air is heated by combustion gases from a conventional burner operating with a hydrocarbon fuel and fresh air needed for fuel combustion under controlled temperature and humidity of the drying air stream entering the product.

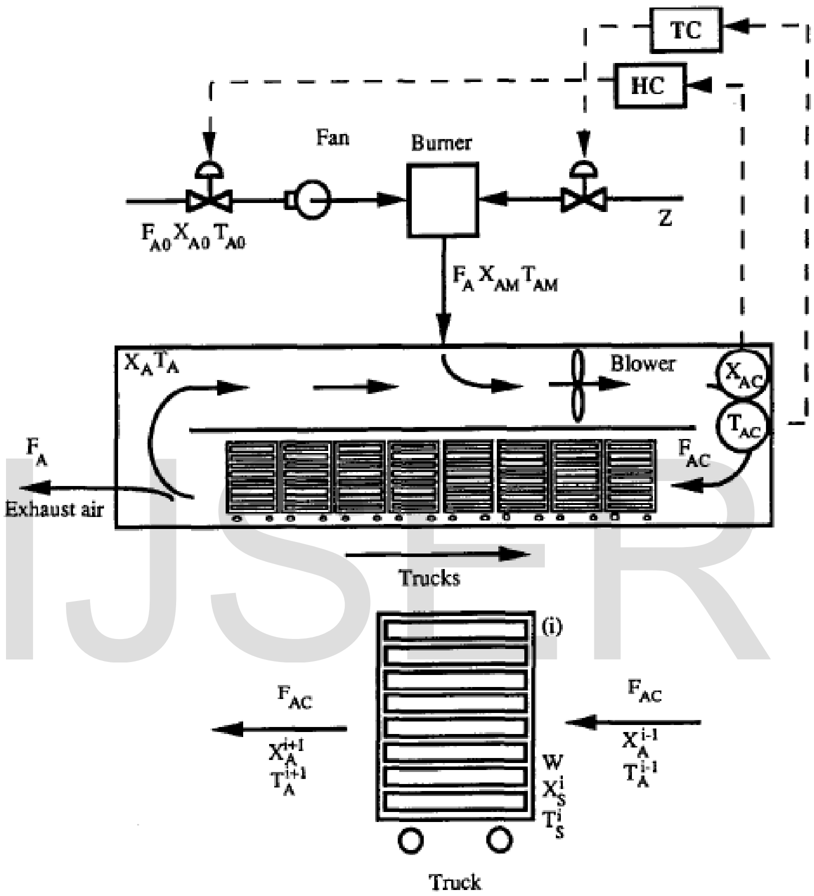

Figure 1. A typical Industrial Tray Dryer (Adapted from Kiranoudis et al. [4])

The development of mathematical model of the tray dryer will obviously take into consideration on one hand the heat and mass balances of air streams and product trays in the dryer and the burner as well as other heat/mass transfer processes taking place during the course of drying. However, the heat and mass transfer phenomena occurring during drying are very complicated processes involving coupled transfer mechanisms within both the solid and the gas phase, and as a result their solution demands considerable computational time. A simplified model is considered in this work, which is tailored for a case study of tray dryer design for plantain. The steps involved in the development of the newly proposed tray dryer design equation used for the programming and simulation are presented below.

Mass of dry sample $M_r = \frac{M_{WF} - M_d}{M_{WF}} \text{ x } 100$ (1)

Mass of water removed $M_{WF} - M_d = 2600 - M_d\ (kg) = 1482kg$ (2)

Total mass of water (M_{TW}): $2600 - M_{bd}$ (3)

where mass of bone-dry material M_{bd} =988

$$C_{PP} = 1.424\ X_c + 1.549\ X_P + 1.675\ X_f + 0.837\ X_a + 4.187\ X_w \text{ [11]} \quad (4)$$

$$X_c = 0.305,\ X_P = 0.013,\ X_f = 0.001,\ X_a = 0.007,\ X_w = 0.674 \text{ [11]}$$

$$\Delta H_v = C1(1 - T_r)^{C2 + C3 \times T_r + C4 \times T_r^2 + C5 \times T_r^3} \quad [12, 17] \quad (5)$$

Where ΔH_v is in J/kmol and T_r is the reduced temperature. The constants are given for water as:

C1 x 10^{-7} = 5.2053 $\Rightarrow$ C1 = 52053000, C2 = 0.3199, C3 = -0.212, C4 = 0.25795

T = ^{o}C + 273.16 in degree Kelvin, T= 333.16k. But

(T_c is $T_r = \frac{T}{T_c}$ 647.10k and T_c = 0.51485) (6)

$$\Rightarrow \Delta H_v = 52053000\ [1 - 0.51485]^{0.279125}$$

But molecular weight of water is: $M = 18.015\ {kg}/{kmol}$

Heat duty is $Q_N = M_P\ C_{PP}\ (T_b - T_{fa}) + M_{tW}\ C_{PW}\ (T_b - T_{fs}) + M_{wr}\ \Delta H_v$ (7)

Where T_A = 65°C, T_{fa} = Room temperature 25°C and $C_{PW} = 4.185\ \frac{kg}{kg_k}$

Power requirement based on 20% heat loss $0.8\dot{Q}_T = 178.193kw$ (8)

The mass flow rate is given as $\dot{M}_{air} = \frac{\dot{W}_{air} = \dot{Q}_T}{Cp_{air} \times \Delta T}$ (9)

Value of CP_{air} at 60°C is 1.009 kJ/kgK from literature.

The volume flow rate of air is $\dot{V}_{air} = \dot{M}_{air} \times \overline{V}_{air}$ (10)

The velocities of the air are $U = \frac{V_{air}}{A}$ and $U_1 = \frac{V_{air}}{A_1}$ (11)

Total head loss = sum of all head losses (12)

Fan horse power $= \frac{\dot{V}_{air} \times H_{TL}}{6356 \times effciency}$ (13)

3. MATLAB SIMULATION METHOD AND CODING

The following steps below illustrate the program workflow of how the program was coded.
Using the MATLAB editor to create a file [18, 19]:
Step 1: Click on **File,** followed by clicking **New** and then click **M-file**
Step 2: on the first line of the **function M-file**, write as:
function variable name = output (variable name)
It is a good practice to use a percentage sign to define the function in order to remember the program after a long time or for anyone to understand the program (nevertheless, this is not a must, as the program will still execute).
Step 3: % define function to be executed
Step 4: Declare all variables (assign variables to all constant values).
Step 5: Base on the number of equations, define all equation or variables to be calculated by separating each by semi-colon as:
Variable name 1 = expression 1; … variable name n = expression n

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Step 6: variable A = input ('please insert the value of variable A ='); Repeat step 6
Step 7: variable B = input ('please insert the value of variable B =')
Step 8: Repeat step 6
Step 9: variable C = input ('compute the value of variable C =')
Step 10: Repeat step 6; variable D_1 = input ('put variable D_1 =') ; ….variable D_n = input ('put variable D_n =')
Step 11: Repeat step 6
Step 12: if variable p > value, disp('character, declare variables')
Step 13: else end
Step 14: Repeat step 6
Step 15: variable p = ('input variable p'); variable = expression
Step 16: end
Step 17: Save the program
Step 18: Run the program by clicking "**RUN"** button**.** Procedures for creating M-function file were cited in literature [18, 19].

The entire design procedure has been programmed using M-Function file in MATLAB version 7.5. When this program below is copied and pasted on the editor window and saved, it becomes executable when the **Run** design button is clicked or when the file name used in saving it is called from the command prompt.

```
function y=desgn(x)
% calculate the mass of dried material
Mr=0.57; a1=0.62; Mwf=2600; Md=Mwf-(Mwf*Mr);
% calculate the mass of water removed during drying
Mwr=Mwf-Md;
% calculate mass of bone dried material
Mbd=Mwf-(Mwf*a1); Mp=Mbd;
Mtw=Mwf-Mbd;
% Determine the specific heat capacity of unripe plantain
xc=0.305; xp=0.013; xf=0.001; xa=0.007; xw=0.674;
Cpp=1.424*xc + 1.549*xp + 1.675*xf + 0.837*xa + 4.187*xw;
% calculate the latent heat of evaporation of water at 60 degree celsius.
% notice the division by 1000 is to convert to kiloJoules
C1=5.2053e+7; C2=0.3199; C3=-0.212; C4=0.25795; M=18.015; Tc=647.1;
Tb=input('please insert the value of Tb='); T=Tb+273.16;
Tr=T/Tc;
Hv=(C1*(1-Tr)^(C2 + C3*Tr + C4*Tr^2))/(1000*M)
% calculate the heat needed to dry the material in KJ
Tfa=25; t=input('please insert the value of t='); Cpw=4.18;
Q=Mp*Cpp*(Tb-Tfa) + Mtw*Cpw*(Tb-Tfa) + Mwr*Hv
% calculate the heat rate required in kiloWatt
Qr=Q/t
% determine the total heat rate to be produced, assuming LP is the percentage loss
LP=input('compute the value of LP='); Qrt=Qr/LP
% to calculate the mass flow rate Ma, the specific volume Sv,
% volumetric flowrate Vfr1 and Vfr.
Cpa=1.009; Doa=1.067;Vk=18.9e-6;L1=input('put L1=');B1=input('put B1=');H1=input('put H1=');
L2=input('put L2=');B2=input('put B2=');H2=input('put H2='); A1=B1*H1, A2=B2*H2
Ma=Qrt/(Cpa*(Tb-Tfa)), Sv=1/Doa; Vfr1=Ma*Sv; Vfr=(Ma*Sv)/4.91747e-4
% calculate the velocity of air first and second and the Raynold number Re
```

```
% respectively respectively
U1=Vfr1/A1,  U2=Vfr1/A2,  Re=(U1*L1)/Vk;
if Re>4000,disp('TURBULENT FLOW, E/D=3e-5, f=0.016')
else end
% determine the first perimeter, the hydraulic diameter and static pressure
% of air due to friction in heating in meters of air
f=0.016; P1=2*(L1+H1); Dh=(4*A1)/P1; g=9.81; ha=f*(L1/Dh)*((U1+U2)/2)^2*(1/2*g);
% determine the static pressure in meters of water for the above static
% pressure
Dow=983.2; hw=((Doa*ha)/Dow)*39.36;
% determine the static pressure due to sudden expansion in meter of air and
% then meter of water.
HL=(1-(A1/A2))^2*(U1^2/2*g); Hl=((HL*Doa)/Dow)*39.36;
% Determine the total static pressure loss
Hm=2.095; Htl=hw + Hl + Hm
% Compute the Horsepower of the fan
eff=input('put eff='); FHp=(Vfr*Htl)/(6356*eff)
end
```

4. RESULTS AND DISCUSSION

The MATLAB simulation results are presented in Tables 1 – 3 as well as Figs. 2 – 4 and are discussed under the effect of dimension, industrial fan's efficiency, time and average drying temperature.

Table 1. The effects of dimensions on the design variables at time of 6 x 3600 and efficiency of 0.75; the parameters ΔH_v = 2.36x 10^3 kJ/kg; **Q** = 3.8487 x 10^6 **kJ; Q_r** = 178.1796 **kW; Q_{rt}** = 222.7246 **kW; M_a** = 6.3068 kg/s and V_{fr} = 1.2020 x 10^4 **cfm** are kept constant.

Dimension (L x B x H)	**(m^2) A_1**	**(m^2) A_2**	**(m/s) U_1**	**(m/s) U_2**	**(inch) H_{tl}**	**(HP) F_{HP}**
1 x 1 x 1 Vs 4 x 2.2 x 2	1	4.4	5.9108	1.3434	6.5099	16.4146
1.2 x 1.2 x2 Vs 4 x 2.1 x 2	2.4	4.2	2.4628	1.4073	2.3385	5.8964
1.2 x 1.2 x 1.2 Vs 4 x 2.3 x 2.2	1.44	5.06	4.1047	1.1681	3.9250	9.8970
1 x 1 x 1 Vs 4 x 2.3 x 2.2	1	5.06	5.9108	1.1681	6.8496	17.2711

From the results presented in Table 1, it is observed that while the all other variables are left constant, an increase in the ratio of the area of the heater housing (Fig. 2) to the drying/cabinet housing leads to a decrease in the velocities of air at both sections and will ultimately lead to a decrease in horse power rating (FHp), meaning cheaper cost of fan. Higher horsepower implies higher purchase cost. Whichever is the case, a bit higher fan horse power than calculated value should always be used for allowance purpose, since dampers can always be used in situation of excess air and are far cheaper compared to fan's replacement [6].

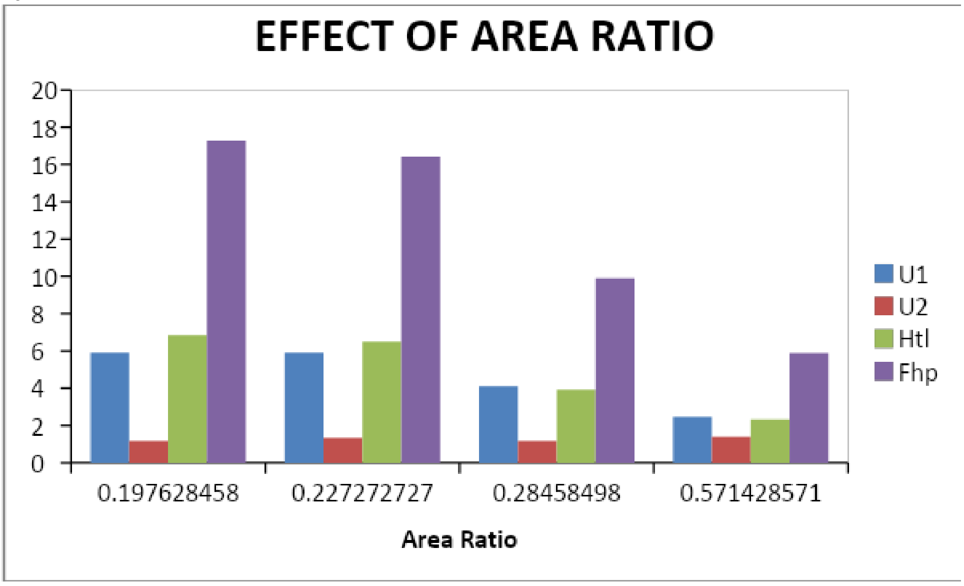

Figure 2. Effect of area ratio (A_1/A_2) on tray dryer design parameters.

Table 2. The effects of fan's efficiency on the design variables at time of 6 x 3600 and dimensions of (1.2 x 1.2 x 2m) Vs (4 x 2.1 x 2m) with the parameters ΔH_v = 2.36x 10^3 kJ/kg; **Q =** 3.8487 x 10^6 **kJ; Q_r =** 178.1796 **kW; Q_{rt}** = 222.7246 **kW; M_a =** 6.3068 kg/s and **V_{fr} =** 1.2020 x 10^4 **cfm** kept constant.

Efficiency	U_1 (m/s)	U_2 (m/s)	H_{tl} (inch)	F_{HP} (HP)
60%	2.4628	1.4073	2. 3385	7.3705
70%	2.4628	1.4073	2. 3385	6.3176
75%	2.4628	1.4073	2. 3385	5.8964
85%	2.4628	1.4073	2. 3385	5.2027

The effect of the fan's efficiency is almost negligible to the entire process, but significant to the horse power of the fan (Table 2). An increase in the efficiency (eff.) leads to a decrease in the horse power rating of the fan which would imply better performance and lower cost while a decrease in efficiency would lead to an opposite effect.

Table 3. Effects of time on design variables at 75% efficiency, dimensions of (1.2 x 1.2 x 2m) Vs (4 x 2.1 x 2m) and constant **ΔH_v** = 2.36x 10^3 kJ/kg and **Q =** 3.8487 x 10^6 **kJ.**

Time	Q_r (KW)	Q_{rt} (KW)	M_a , kg/s	V_{fr} (CFM)	U_1 (m/s)	U_2 (m/s)	H_{tl} (inch)	F_{HP} (HP)
6 hrs	178.1796	222.7246	6.3068	1.2020 x 10^4	2.4628	1.4073	2.3385	5.8964
5 hrs	213.8156	267.2695	7.5682	1.4424 x 10^4	2.9554	1.6888	2.4456	7.3998
4 hrs	267.2695	334.0868	9.4602	1.8030 x 10^4	3.6942	2.1110	2.6428	9.9956

From Table 3, the results of the simulation show that time is the second most effective variable after temperature in the sense that it causes a change in almost all the variables apart from the latent heat of water (ΔH_v) and the heat duty (Q) which are independent of time. The significance of this is that trying to achieve dryer at an earlier time would imply higher high cost of power generation and fan purchase. It is recommended that for drying of plantain, the drying should not be achieved earlier than four hours to avoid case hardening.

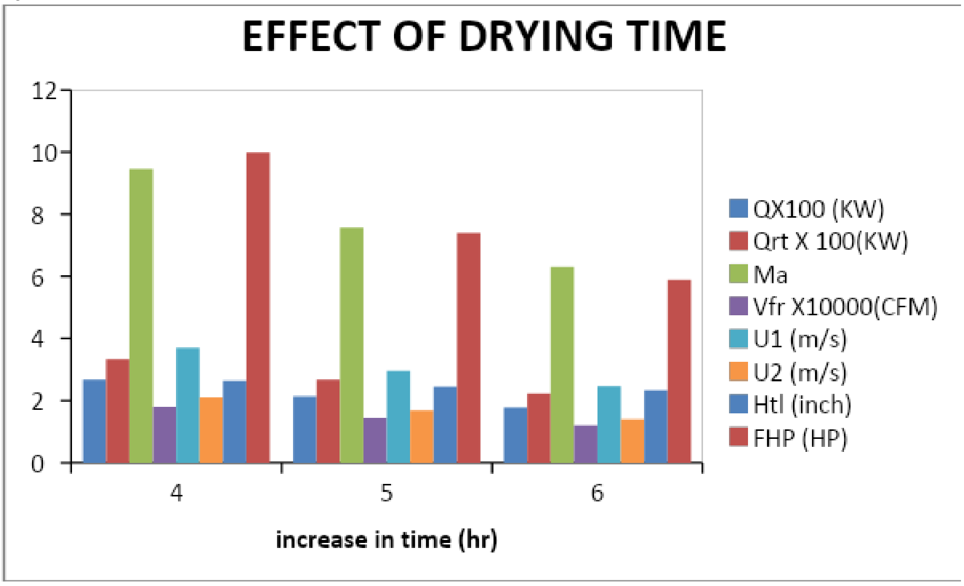

Figure 3. Variations of drying time with various design variables at 75% efficiency and dimensions of (1.2 x 1.2 x 2m) Vs (4 x 2.1 x 2m).

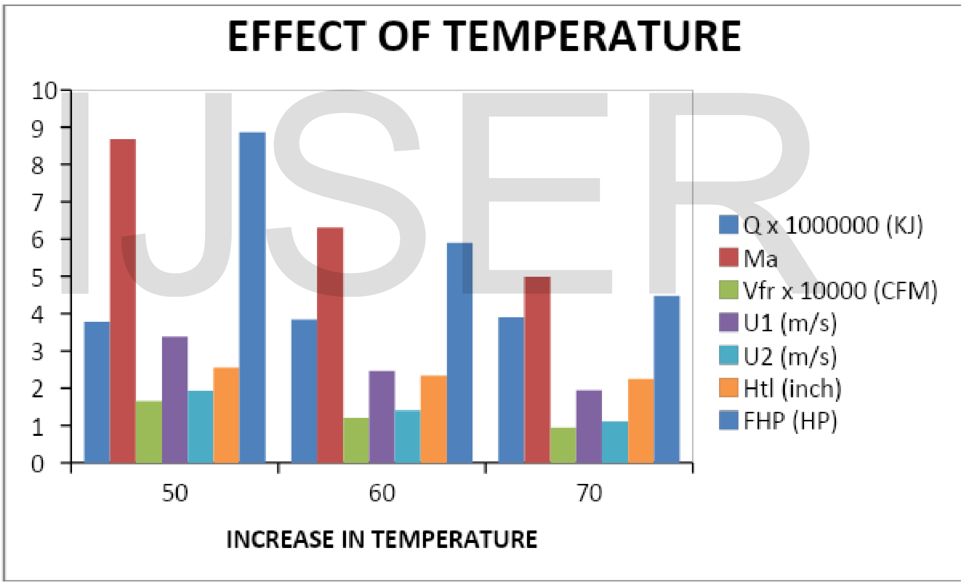

Figure 4. Variations of drying temperature with various design variables at 75% efficiency and dimensions of (1.2 x 1.2 x 2m) Vs (4 x 2.1 x 2m).

Evident from the chat in Fig. 4 on the effect of drying temperature is the fact that temperature is the most effective parameter or variable, wherein a change in temperature leads to significant variations of all the variables. The significance of this is that achieving drying at higher temperature implies higher cost of power generation and lower cost of fan when other parameters are unchanged. This is in line with what was reported in the literature [7].

5. CONCLUSIONS

The major parameters of a tray dryer have effects on one another and in turn, on the drying process. Temperature was found to be the most effective parameter, seconded by time. A change in temperature alone caused a significant change on all other variables. Although a combination of parameters is needed for quality drying, it was discovered that with only temperature control the other factors. As different material has different drying properties, care should be taken to avoid case hardening. This research would therefore be useful for both small and large scale plantain processing industries using tray dryers to gain insight at what temperature to operate on in order to obtain good product quality when other factors are arbitrary specified and also to eliminate the stress or rigour of trying to control too many tray dryer parameters when just one (temperature) solves the problem.

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